ELECTRIC SERVICE DISTRIBUTION SYSTEMS

THEIR DESIGN AND CONSTRUCTION

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PREFACE TO THIRD EDITION

This edition appears under the title "Electric Service Distribution Systems," instead of the title "Electric Central Station Distribution Systems."

It is felt that the new title more correctly describes the subject matter of the book, in view of the growth of electric service systems to a state in which they are served from several stations and interconnected by tie-lines to form a system, rather than from a single central station.

In the decade which has intervened since the second edition was prepared, the use of electricity for light, power, transportation, and other purposes has increased until, in settled communities, the home, the shop, and the factory have generally adopted electric service, and extensions are rapidly reaching rural communities.

In the cities, the average load per block has become such, in many sections, as to introduce new problems and to necessitate reconsideration of many long established practices.

This has resulted in numerous revisions in this edition and a complete reconsideration of the treatment of alternating current distribution through secondary networks, the developments made in high-voltage cables and of the heating of cables in underground conduit systems.

PREFACE TO FIRST EDITION

This volume is the result of a group of articles which appeared serially in the *Electrical Age* during the years 1908 and 1909, covering various phases of Central Station Distribution Work. The preparation of these articles was undertaken by the authors because of repeated requests from young engineers engaged in distribution work for information bearing on many of the details of their work.

While there were various treatises dealing with special subjects such as low-tension networks, transmission of power, storage batteries, etc., quite fully, there appeared to be no treatise covering the general field of distribution from the standpoint of American practice to which young engineers and students could be referred. The material of the original articles revised and somewhat extended is presented in this volume. Two chapters have been included for convenient reference at the close of the book, in which are compiled such tables as are likely to be needed by the distribution engineer, together with a brief outline of the laws of electric circuits. The treatment is based upon the assumption of a general knowledge of electrical theory such as is possessed by the more advanced students of engineering and by men in practical distribution engineering work. Much of the subject matter of the book is, however, of such a nature as to be easily grasped by practical men who have not had a full theoretical training.

Distribution problems are usually capable of more than one solution, and the decision as to which is best is often determined by local conditions which cannot be made sub-

servient to general rules. It is therefore difficult to generalize upon many phases of the subject, and frequent use has been made of such qualifying phrases as "in most cases," "usually" or "under some circumstances."

The subject matter has been treated entirely from the American point of view, as the book is intended for American Engineers. European methods differ so much from those followed in America, owing to differences in the conditions under which electric lighting properties are owned and operated there, that it was not felt that their consideration would be of especial value.

THE AUTHORS.

CHICAGO, 1910.

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ELECTRIC SERVICE DISTRIBUTION SYSTEMS

CHAPTER I

SYSTEMS OF DISTRIBUTION

Series Systems. — The arc lamp was the first practical device for converting electrical energy into light. It was developed by Brush in Cleveland in 1876 and later by Thomson and Houston and others.

The early arc systems found a ready application in the lighting of city streets. The large areas to be covered by street-lighting circuits led naturally to the high voltage series system as the most economical in first cost.

Special direct-current generators equipped with automatic regulators to maintain the current constant as the number of lamps in circuit varied, were required.

The lamps were designed to burn carbon electrodes which were consumed after about twelve hours' burning with a current strength of about ten amperes. Later, seven-ampere generators and lamps were designed in response to a demand for a less expensive light, and arc-lighting systems were extended to general commercial lighting.

Following the year 1895, the enclosed arc lamp burning carbon electrodes in an inner globe, so designed that a very small supply of air could enter, was brought to a commercial stage of development. These lamps required trimming only after sixty to eighty hours' burning, and so permitted a re-

duction of 75 to 80 per cent in the expense of carbons and lamp trimming labor. They therefore became standard and were substituted for open arc lamp systems very generally during the following decade.

During this period of change from open to enclosed lamps, advantage was taken of the use of alternating current for arc lighting purposes. The special direct-current generator was replaced by a transformer receiving energy at the standard system voltage and delivering it to the circuit at the voltage required to maintain a constant current of the desired strength at full load.

This resulted in a considerable saving in the cost of series lighting equipment, since the main generator capacity of the alternating current systems cost very much less per lamp than the relatively small series arc machines which were required for the direct current systems.

There was also a greatly reduced building expense since the floor space required for the shafting and belting of the numerous arc machines was excessive.

The series regulating equipment could be placed in substations in various parts of a large city, thus shortening the average length of arc lighting circuits.

In some cases where there was too large an equipment of the better types of arc machines installed to be scrapped, the shafting and belting were displaced by alternating current motors, each driving a pair of arc machines. These systems at first used direct current enclosed lamps, and later magnetite or flaming arc lamps. For a time, this gave them some advantage over the alternating current systems which could not use the high efficiency direct current lamps without adding rectifier equipment. Mercury arc rectifiers were installed for this purpose where it was desired to get this benefit.

With the development of suitable flaming arc lamps for 60 cycle alternating current service, the necessity for recti-

fying equipment disappeared, and the alternating current series system became the simplest and most economical form of series distribution.

This system may be used equally well for series incandescent lighting and has become standard for new installations.

Series alternating-current systems using enclosed lamps are operated at 6.6 to 7.5 amperes, 6.6 amperes being the most common current strength.

The rapid advance in the development of the tungsten incandescent lamp brought this form of lighting into close competition with arc lamps for all kinds of street and public space lighting, and thus supplanted arc lighting.

The tungsten lamp, by reason of the wide range of sizes of units in which it can be made, is found as readily adaptable to the lighting of business districts using the larger units as to the lighting of residence districts with smaller units.

Tungsten units of 300 to 500 watts have been substituted for 450 watt alternating current enclosed arc lamps effecting a saving in operating cost and a materially improved illumination.

The life and efficiency of these units has been notably increased on series circuits by the use of a small compensator coil in the hood of the lamp which steps the current up from the standard current strength of the circuit to about 20 amperes in the lamp filament.

In the lighting of business districts where great intensities are essential the tungsten lamp in sizes of 750 to 1000 watts has advantages over the arc lamp which are resulting in the displacement of the arc lamp for this service.

In residence and suburban districts where shade trees demand the use of units distributed more frequently, the smaller sizes are most economical.

Application of Series Systems. — Since the lamps supplied by a series circuit are operated at constant current, it follows

that the voltage impressed upon the circuit terminals must be varied as energy consuming devices are switched into or out of the series. With circuits operated at 6.6 amperes, the pressure absorbed at the terminals of a 500 watt arc lamp is about 75 volts, and the circuit must be operated at about 7500 volts when carrying 100 of these lamps.

A constant current circuit is thus, inherently, a high potential circuit and lacks the elements of safety and convenience afforded by low potential systems for the lighting of buildings.

The use of constant current systems for interior lighting which was common in the earlier years of the industry has therefore steadily decreased, and following the introduction of the tungsten lamp, practically disappeared.

Series distribution has found a wide field of application in the field of street and park lighting. The conditions obtaining in such lighting are that the load density runs from 5 to 10 kw. per mile of street and the lights must be switched on and off at a given time each day.

The switching requirements favor the use of separate circuits, controlled at the point of supply.

On the contrary, the low load density favors the absorption of the street lighting load on the general lighting system as far as possible.

Where the general light and power system does not fully cover the district in which the streets are to be lighted or where alley routes are largely used, it is sometimes more economical to run separate circuits on the streets to be lighted. Where there is no general supply as in park and boulevard lighting, it is usually necessary to provide separate circuits in any event, in which case the series system is usually the more economical.

In the central parts of larger cities, street lighting is often supplied from the general system, the switching being done more economically by patrolmen.

Types of Series Circuits. — The routing of a series lighting circuit is fixed by

(*a*) the location of the lamps,

(*b*) the geographical arrangement of streets and alleys and

(*c*) the requirements of operation and maintenance.

Having the locations of the lamps fixed, the problem of circuit design consists in so routing the circuit that it will require a minimum length of conductor consistent with requirements of continuous service.

The series system is subject to the inherent weakness that a break on any loop of the circuit interrupts the service on the entire circuit. With circuits having 5 to 10 miles of conductor the location of a break may require considerable time, during

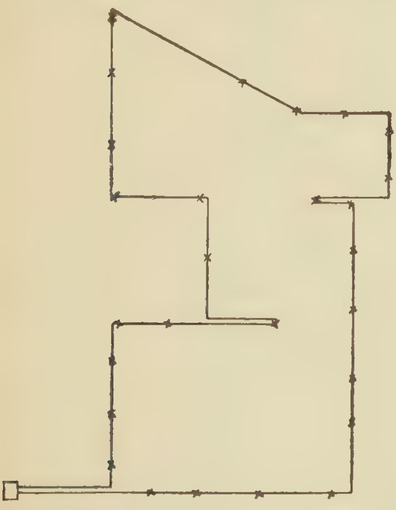


Fig. 1. Open Loop Series Circuit.

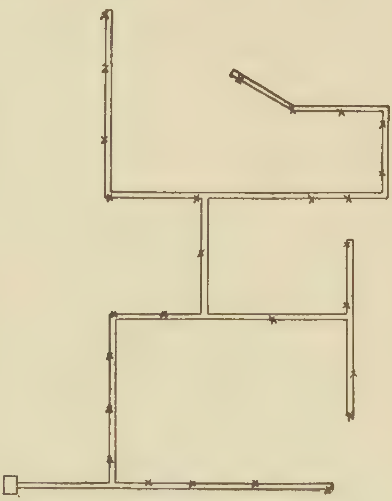


Fig. 2. Parallel Loop Series Circuit

which several miles of streets are in darkness unless facilities for testing are provided at several points on the circuit.

A circuit may be laid out on the open loop plan as shown in Fig. 1, or on the parallel loop plan as in Fig. 2. The open

loop circuit proceeds away from the point of supply through one section of the city and returns through another district. Consisting of but one wire, it is constructed with the minimum of conductor mileage. But in case of a break there is no provision for making a test to locate the trouble, and the circuit must be traversed until the break is located.

With the parallel loop plan the wires are together so that a jumper connection can be made at any one of a number of points. When a break occurs the circuit can be quickly closed through the remaining lamps and only those lamps on the broken loop are out. The provision of several test points

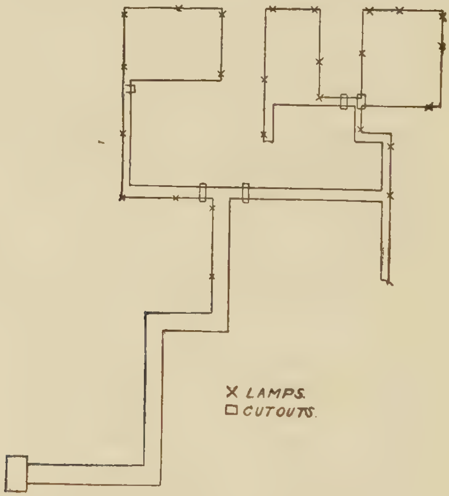


Fig. 3. Mixed Loop Series Circuit.

on a circuit thus enables a repair man to locate the broken loop promptly and restore service on the remainder of the circuit before the break is repaired.

When continuity of service is important, the use of open loop should be limited to relatively small areas, as in Fig. 3, and the circuits should be equipped with convenient facilities by which tests can be quickly made. With alternating

current the use of extended open loops is likely to be the source of trouble with telephone and other signaling circuits.

Series Cutouts. — The type of switch required for the control of lamps or groups of lamps on a series circuit must be such that it will short-circuit the loop which is to be cut out, and remove the short-circuit when the loop is to be cut in. The capacity of the " cutout," as it is commonly known, is determined by its ability to open the short-circuit across a loop, without allowing the arc to carry across the terminals.

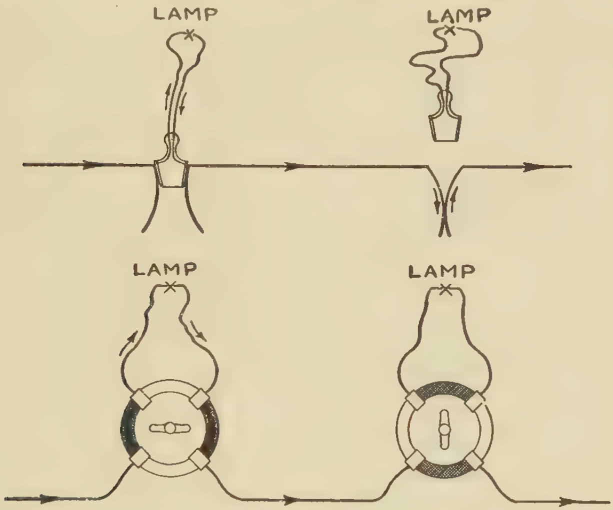


Fig. 4. Types of Series Cutouts.

Its current-carrying parts are ordinarily more than ample when made sufficiently rugged for mechanical strength.

It is desirable that the loop which is switched out be completely isolated from the working circuit, for the safety of repair men. The cutout is therefore usually so constructed as to both short-circuit and disconnect the loops and in this form is known as an " absolute " cutout.

Various mechanical arrangements have been devised by which loops can be absolutely cut out, two of the more common being shown in Fig. 4 as used in overhead construction. When lead covered cables are brought into the base of a lamp pole, a combination pothead and cutout such as that shown in Fig. 5 has been found very useful.

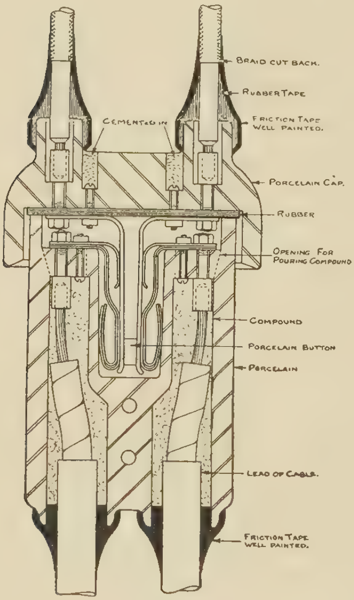


Fig. 5. Series Cutout. Pothead Type.

Alternating Current Series Systems. — Alternating current series systems are employed very generally in connection with incandescent lamps for street and park lighting. This is in part due to the desirability of using smaller units with closer spacing than is usual with arc lamps and in part to the greater simplicity of incandescent lamps in maintenance and renewals.

The alternating current series transformer or compensating coil affords greater flexibility in the selection of lamp sizes and removes the hazardous high potential at the lamp-post giving greater safety in operation.

Series alternating current systems may be classified as (*a*) constant-current and (*b*) constant-potential systems.

The constant-current system is one in which a regulating transformer is employed to hold the current at a fixed value when lamps are cut in or out of the circuit. This was developed for arc lighting service and has been employed for incandescent lamp circuits quite generally.

The constant-potential series system is one in which the circuit is made up of the proper number of units to take the normal current of the lamps while the supply voltage remains constant. No regulating transformer is employed to vary the circuit voltage with changes in load, though a fixed inductance is sometimes used to limit the current in case a considerable part of the lamps in the circuit are short-circuited.

By the use of series transformers it is possible to use certain combinations of series circuits which have operating advantages of great value. These consist of local series circuits of groups of lamps within one or more city blocks which are supplied by series-transformers on the main series circuit. Thus the voltage of the lamp circuit may be kept low enough to be handled safely by operating men and to remove much of the hazard to the public when posts are broken off or circuit wires exposed in other ways.

A further advantage is found in that the series transformer for the local circuit, being interposed between the local circuit and the main circuit, acts as a protection to the main circuit in case of a break in the continuity of the local circuit. This may be arranged to greatly reduce the length of the main circuit, thus reducing very materially the hazard of breaks and grounds on the main circuit.

Where the main series circuit is carried underground several of the series transformers may be grouped in a single manhole from which the local circuits are carried in parkway cable or by overhead lines. In other cases they are placed on poles on main thoroughfares with the local circuit carried along the side streets as required by lamp locations.

This system is illustrated in the arrangement of circuits in Figs. 6 and 7 which has been used extensively in the city of Chicago and elsewhere.

In the Chicago system the street lighting is supplied from sub-stations to which energy is transmitted at 12,000 volts

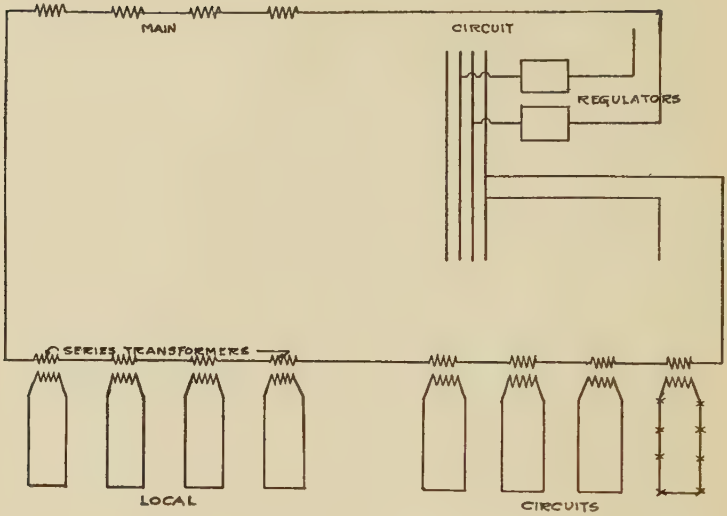


Fig. 6. Local Series Secondary Circuits.

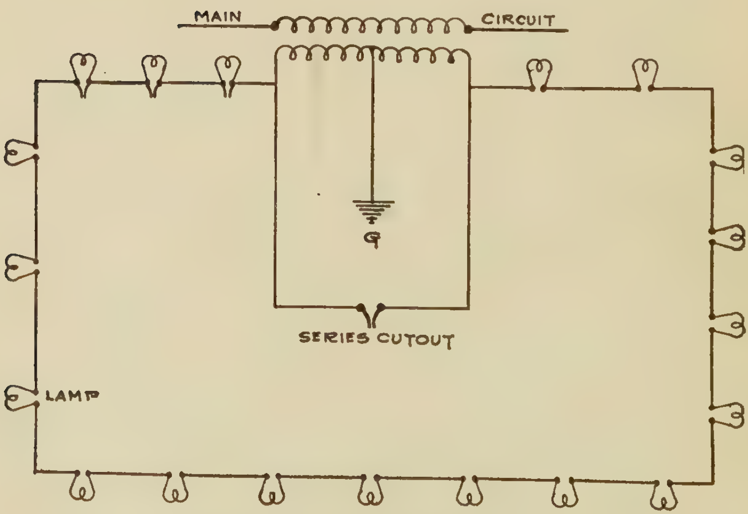


Fig. 7. Local Series Circuit.

three phase by underground cables. In these sub-stations it is transformed and delivered to the main series circuits through constant-current regulators.

The main circuits are supplied through constant-current regulators at about 5000 volts and are regulated for a current of 6.6 amperes. These circuits supply individual lamps of 300 to 500 c.p. on business streets and groups of 100 c.p. lamps in residential districts.

On business streets the lamps are mounted on trolley poles where available and are supplied by overhead lines carried on the trolley poles. The circuits are carried underground from the point of supply to the streets where lighting is served. In residential streets the main circuit is placed in a conduit line and supplies groups of four series transformers placed in vaults at street intersections. From these local transformers circuits of parkway cable are laid along each side of a city block, each circuit supplying about 20 lamps carried on iron posts 10 feet high at the curb line. The lamps are spaced about 150 feet apart, and the posts are alternated on opposite sides of the street. This gives a working voltage of about 350 on the terminals of each local transformer.

The transformers are so designed that in case a local circuit is opened by a break in the cable, the secondary voltage will at once rise to about 1000 volts and puncture a film cutout placed across the secondary terminals. This short-circuits the local circuit, but in no way affects the service on the other local circuits supplied from the main circuit. In case of the failure of a lamp filament the continuity of the local circuit is maintained in the same way by the puncture of a film cutout placed across the lamp terminals.

The regulation of the current strength is best accomplished by the transformer type of regulator with movable coils.

This varies the impedance of a circuit in such a way as to

hold the current constant when lamp resistance is added to or cut out of the circuit.

Inductance is used in preference to resistance for this purpose to maintain efficiency. The inductance being added in quadrature with the circuit voltage varies the power factor, making it lower at fractional loads. At full load the inductance is made about 40 per cent of the circuit supply voltage, giving a power factor of about 90 per cent.

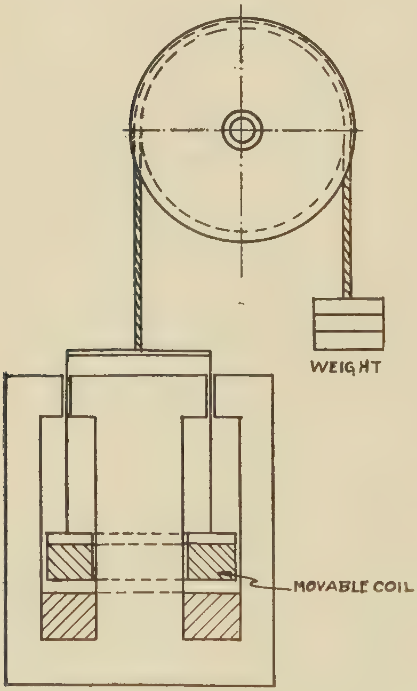


Fig. 8. Constant Current Regulator.

The variable value of inductance is usually secured by means of an arrangement of coils similar to that shown in Fig. 8. The secondary coil is movable in a vertical plane and is counter-balanced by a weight so adjusted that the position of the coil is varied by the repulsion between primary and secondary as the load is varied on the circuit. As the distance between the coils is increased the magnetizing current increases, thus increasing the inductance in the primary circuit. The voltage of the secondary is reduced by the increase of magnetic leakage as the distance between coils is increased.

In another type of regulator which has been used to some extent the variation of inductance is secured by changing the position of the iron core of a regulating

coil, which does not act as a transformer but as a reactance only.

The *constant-potential* series system has been extensively used, notably in the City of Milwaukee, Wisconsin.

In the Milwaukee system, power is taken from the general service distribution system at a number of convenient points. This results in an arrangement by which groups of 5 to 6 local transformers at constant-potential are grouped together. From these points series circuits are carried to the lamps in the surrounding district.

The voltage is raised from the usual distribution voltage to about 4000 volts for the series circuits, each circuit being isolated from the others by a separate transformer.

The control of the lamps is effected by a time clock on the main primary connection, where also a meter is placed by which the charge for energy is determined.

These " sub-stations " are placed on a pole supported platform where circuits are overhead, or in a suitable vault where underground circuits are used. At each lamp is placed a series transformer by which the voltage is lowered to the lamp voltage. These transformers are provided in several standard sizes so that different sizes of lamps may be carried on the same circuit by selecting the proper size of transformer. Thus residential and business streets are supplied from the same circuits where it is convenient to use circuits for both purposes.

The series transformer is placed in the ground at the base of the lamp pole and is embedded in asphalt to exclude moisture.

The points of supply are more numerous in this installation than is the case where circuits are controlled from a sub-station which is operated by an attendant. The length of the circuits and the cost of installation are therefore reduced as compared with a system including attended sub-stations.

Constant-current regulators, suitable for use out of doors, are available for installations drawing their energy from a general distribution system and constant-current circuits are sometimes used in this way.

The difficulty of maintaining clocks has led to the use of other methods of remote control in some cases.

The use of one circuit controlled by hand to switch others through relays has been resorted to at times.

This can be extended in cascade form so that the current passing through one circuit actuates a relay which closes the next circuit and so on. The relay is so constructed that the stoppage of the current in any circuit opens all the circuits beyond it. This is, of course, a disadvantage when a break in one circuit opens several other circuits.

The value of such systems is dependent largely upon the geographical arrangement of neighboring circuits and their source of supply. In many cases additional wire is required to bring the circuit and its relay to the proper point to control the neighboring circuit.

Protective Methods. — Series circuits should be protected by the use of a separate transformer at the source of supply isolating them from each other. This is necessary to prevent parts of two circuits being shunted out at times when grounds occur at two points simultaneously. Where constant-current regulating transformers are used these serve in the double capacity of isolating transformer and regulator.

Constant-current circuits are protected from interruption due to failure of a lamp filament by the use of a film cutout placed at each lamp. These cutouts are so designed that the film is punctured at about 400 volts and when this occurs the lamp is short-circuited, thus restoring continuity.

These cutouts are also used on the secondaries of series transformers when they are used to supply a local series

circuit to protect the transformer from the high potential of an open circuit in case the circuit is broken elsewhere than at a lamp.

Film cutouts are not applicable to a constant-potential series circuit without regulator control since the shunting of a lamp would increase the current in the remaining lamps proportionately and thus shorten their life.

In such systems, the individual lamp must be protected by a "compensating coil" or transformer across the lamp terminal. This transformer is so designed that the iron core is saturated when a lamp filament fails and the voltage absorbed is sufficient to hold the current at its normal strength. This may be done by a suitable design in such a way as to hold the current practically constant when 10 to 15 per cent of the lamps are out.

These lamp transformers serve the additional purpose of reducing the voltage to a safe value at the lamp pole and of isolating the lamp from the high voltage circuit.

The mid-point of series circuits which are carried in underground cable is sometimes grounded for the purpose of limiting the potential to ground in case of accidental grounds occurring near either of the supply terminals. However, when an accidental ground occurs the lamps between the point grounded and the mid-point are shunted out and such an arrangement can only be used where circuits are equipped with constant current regulators. With cable circuits a ground point is sometimes provided at the midpoint for testing purposes. This is equipped with disconnecting potheads by which necessary changes in connections are readily made. In cases where multiple conductor cables are used carrying several circuits in one cable disconnecting potheads are found very useful at the branching points as a means of testing the circuits individually.

The potential to ground may also be limited by connecting the two halves of the winding of the circuit transformer as shown in Fig. 9. The occurrence of grounds, when this connection is used, does not raise the potential of lamp fittings

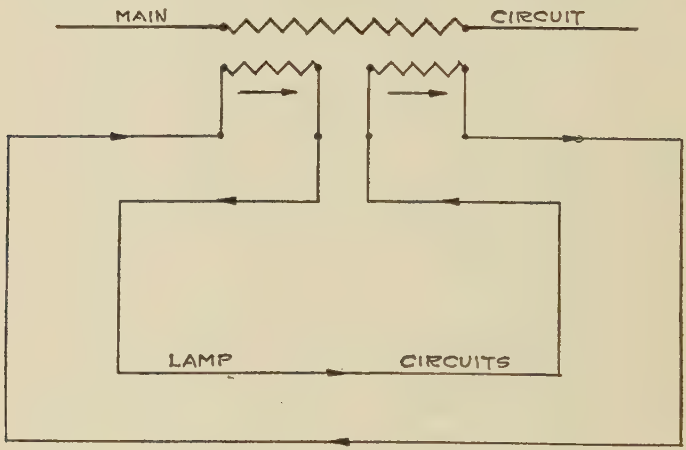


Fig. 9. Series Circuits, Low Voltage.

to more than half the circuit voltage and the permanent grounding of the midpoint of the circuit is avoided.

This connection is a desirable one for use on local series circuits, operating at approximately 300 volts, as it limits the potential to ground to 150 volts and greatly reduces the danger of shock to operators and the public.

The duct space in underground lines is conserved by the use of multiple conductor cable for the main circuit runs from the point of supply to a point in the district served from which the circuits are allowed to diverge. In this way four to six circuits may be carried within one lead sheath, with a color scheme in the insulation to facilitate identification at terminals. Disconnecting potheads, such as that shown in Fig. 10, are provided at each end to permit ready testing or isolation when required.

Multiple Systems. — The comparatively large unit required for arc lighting rendered it unfit for interior lighting of many kinds and led to a demand for a "subdivided" form of light, which could be used in houses, offices and stores,

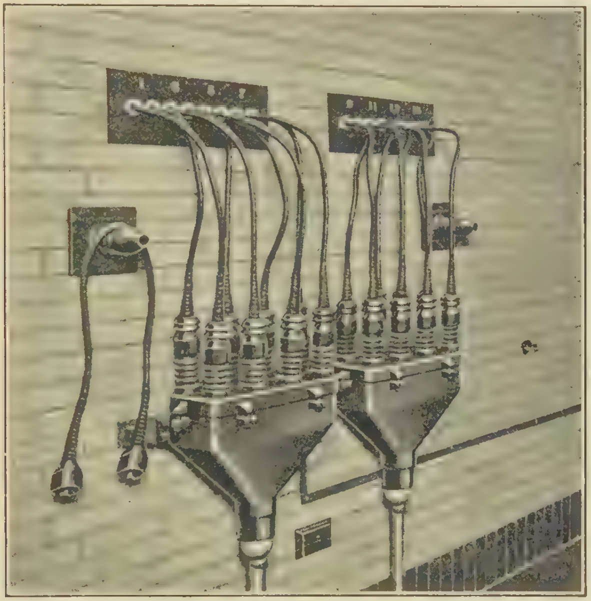


Fig. 10. Multi-Conductor Potheads.

as a substitute for gas and oil lamps. The high voltages inherent to series systems made them unsafe to life and property, and suggested the desirability of a multiple system operating at a voltage low enough to be safe and easy to handle, and yet high enough to be commercially feasible.

These considerations led Thos. A. Edison to enter upon a long and most thorough search for materials which could be made into an incandescent type of lamp. His untiring zeal and native genius finally produced incandescent lamps which

would burn for a sufficient length of time to be considered commercially practicable.

Having solved the problem of subdividing the electric lamp, he next turned his attention to the development of a multiple system of distribution by which it could be made available to the world. This involved a suitable lamp socket and base, safety fuse cutouts to protect from short-circuits, switches of all sizes, generators, motors, and various wiring fittings none of which were then available.

The necessity of using underground construction further required the development of the "tube" system of mains and feeders, together with junction boxes and fittings.

The first electric central station for incandescent lighting in America was put into operation in October, 1882, in New York. This was the first station of the Edison Illuminating Company of New York. These first systems were operated at about 110 volts on the two-wire plan. Direct current was used because of the lack of knowledge of alternating-current motors and transformers, and the ready adaptability of the direct-current motor to variable-speed machinery.

The voltage was fixed at about 110 by the inherent nature of the incandescent lamp filament, which in the early stages of the art could not be made to give 16 candle power at much more than 110 volts without reducing the life of the filament below commercial limits.

The excessive cross-section of copper used to deliver electricity in the quantities demanded and at the distances required led Edison to devise his three-wire system. This system which is widely used at present is based on the operation of two generators in series with a third wire connected between the machines. This permitted the use of 110-volt lamps and yet gave the advantage of 220-volt distribution when the load was evenly divided on the opposite sides of the third or neutral wire. Its invention permitted a saving in

conductor copper of over 60 per cent and doubled the radius of distribution.

This system was adopted for use in the central parts of most of the larger American cities and in many of the cities of Europe, and was designed for installation underground, since municipal regulations required it in most large cities.

The adaptability of the direct-current motor to elevator and other variable-speed power work, and the possibility of utilizing the storage battery as a reserve in case of emergency, have made it desirable to retain the direct-current systems in the central parts of most of the larger cities where they were originally established.

The excessive investment required to extend low potential lines into the parts of a city where the load is scattered and the necessity of establishing several generating stations in the large cities, thus increasing the cost of operation, led inventors to turn their attention to the development of alternating-current distributing systems by which higher voltages could be used with transformers. The first alternating-current system was put into operation at Greenburg, Pennsylvania, in 1886, by the Westinghouse Company. Thomson and Houston added an alternating-current system to their series arc system which had been very successful, and others followed.

These systems were designed to operate at 125 to 133 cycles, 1100 volts, single-phase, and were installed in medium-sized cities where the direct current had not been established, or in the outlying parts of those cities which were being served with direct current in their central portions.

As these systems developed, the demand for power service became greater and the plants needed a day load to make them profitable. The single-phase motor was not satisfactory at 125 cycles in any except the smaller sizes, and the alternating-current systems were greatly handicapped on this

account. In 1888, Tesla brought out his polyphase system, in which two, three or more single-phase circuits were arranged to operate with a definite phase displacement between them. This permitted the use of a simple form of self-starting motor which could be made in any desired size. Being of a rugged character its maintenance was less expensive than that of the direct-current and other commutator types of motors.

The Tesla system was introduced in America by Westinghouse. His engineers selected the two-phase system as being the best suited to general distribution work, chiefly because the problem of balancing two phases in a small system presented the fewest difficulties.

Experience had demonstrated that a pressure of 1100 volts was too low for satisfactory service in the larger systems and a standard of 2200 volts was therefore adopted.

The design of polyphase motors was found to be much more satisfactory at 60 cycles than at 125, and this was true of arc lamps and other apparatus having coil windings. The two-phase system was therefore developed for 2200 volts and 60-cycle operation.

The three-phase system was used at first only in the transmission of large amounts of power at higher voltages than were used in distribution work.

Where two-phase generators constituted the source of supply the energy was transformed into three-phase for the purpose of transmission by a special method of connections devised by Charles F. Scott, then an engineer of the Westinghouse Company.

Later the three-phase system was made more generally available and was adopted for distribution in some of the larger cities where the problem of balancing was not difficult because of the larger loads involved. Thus it came about that both two-phase and three-phase distribution systems are in use in the larger American cities.

The value of three-phase transmission for large amounts of energy was soon recognized by the engineers of the larger direct-current systems, who were in need of some means of consolidating numerous small steam plants into one or two large generating stations, to reduce the cost of production. This was accomplished by the introduction of rotary converter substations receiving high-tension three-phase energy and converting it to direct current at 110–120 volts for distribution.

The first American installation of this character was designed by Louis A. Ferguson and was put into operation in Chicago in the year 1897. It was operated at 2250 volts, and 25 cycles, three-phase, and carried a load of about 200 kw. permitting a steam plant to be shut down except during the heavy load period in the evening.

This was very shortly raised to 4500 volts and later to 9000 volts as the system was extended.

The 25-cycle frequency was adopted because of the more satisfactory operation of synchronous converters at the lower frequencies, and this was standard for systems where the larger part of the energy was converted to direct current for distribution, for some years.

It was too low, however, for use with arc and incandescent lamps directly and the adoption of 60 cycles as a standard frequency for alternating-current distribution rendered it necessary to provide motor generator sets as the converting medium where alternating current supply was derived from a 25-cycle transmission system.

These frequency changer substations were later supplemented in some of the larger cities by transformers supplied from a separate 60-cycle generating system. The lower efficiency and higher first cost of frequency changing sets as compared with transformers made it desirable to establish separate generating and transmission systems for the 60-cycle

supply as soon as the 60-cycle portion of the load became large enough to justify an economical size of generating unit.

Various transmission voltages were adopted, 6600 being used in New York, 9000 in Chicago and 13,200 in some of the other large cities. In Boston, Chicago and other cities voltages of 20,000 and upward were later adopted for use in transmission to suburban districts. As a result of this gradual development several systems of distribution are found in general use in American cities, the advantages and disadvantages of which will be considered.

Single-Phase. — This is a two-wire system and therefore the simplest to install and maintain of the alternating-current systems. When used for distribution in cities it is commonly operated at 2200 volts and 60 cycles.

The investment required for feeder copper is 33 per cent more than for a three-phase feeder, other things being equal. This is true of the distributing mains only where there is a high load density, that is, where the load is sufficient to require the use of primary mains larger than #6 A.W.G. The mains must be of a minimum size for mechanical strength (usually No. 6 or No. 4) and in scattered districts, the third wire required for a three-phase system adds 50 per cent to the cost of copper if three-wire or 100 per cent if four-wire without a commensurate gain in efficiency of distribution.

The use of single-phase distribution in such districts is also most economical from the standpoint of transformer investment. The division of a scattered lighting load between three phases decreases the average size of transformers, thus increasing the investment and iron losses.

It is therefore usual to retain the advantages of single-phase distribution in polyphase systems by making the branches which supply no large power, single-phase.

The chief limitation of single-phase distribution as applied to all purposes is that single-phase motors are much more complicated and expensive than polyphase motors and their

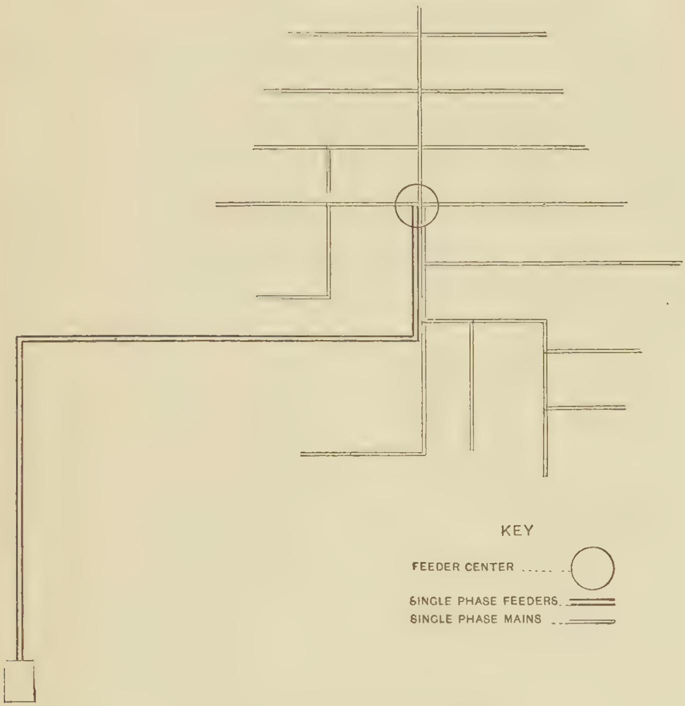


Fig. 11. Single-phase Feeder.

use is limited to the smaller sizes. A single-phase feeder is shown in Fig. 11.

Two-phase Systems. — In two-phase systems the generator delivers two separate currents, one of which is a quarter cycle behind the other. Hence the name quarter-phase is sometimes applied to these systems.

When the two parts of the system are operated electrically

separated from each other, four wires are required. Under these conditions the circuits are virtually single-phase as far as their capacity for the transmission of energy is concerned. Where used to supply the windings of a two-phase motor through suitable transformers, the displaced phase produces a torque which makes the motor self-starting without special commutation or split phase coils, such as are necessary with single-phase motors.

Where used for general lighting and power distribution, the lighting taps are made single-phase and balanced on the two phases with approximate equality. The four wires are carried along the principal thoroughfares and in such other places as the demand for large power service requires. Consumers using less than 5 horse-power are usually required to provide single-phase motors, on account of the extra cost of transformers and line wire required for small two-phase service.

With inductive loads the drop on the two phases is not symmetrical and this tends to produce an unbalanced pressure condition on motor circuits.

The two-phase system requires but two transformers for power service. In this respect it has an advantage over the three-phase system. Where the amount of power served is less than 25 to 30 horse-power, two transformers may be used in either the two-phase or the three-phase system, but in larger installations, there is a saving in transformer investment in two-phase installations due to the average size of units being larger and to the ability to adjust transformer capacity to maximum demand somewhat more closely. Thus in a two-phase installation, a demand of 85 kv-a. could be taken care of by 2–40 kv-a. units while in three-phase work, this load would ordinarily require 3–30 kv-a. units, costing about 20 per cent more than the two-phase installation.

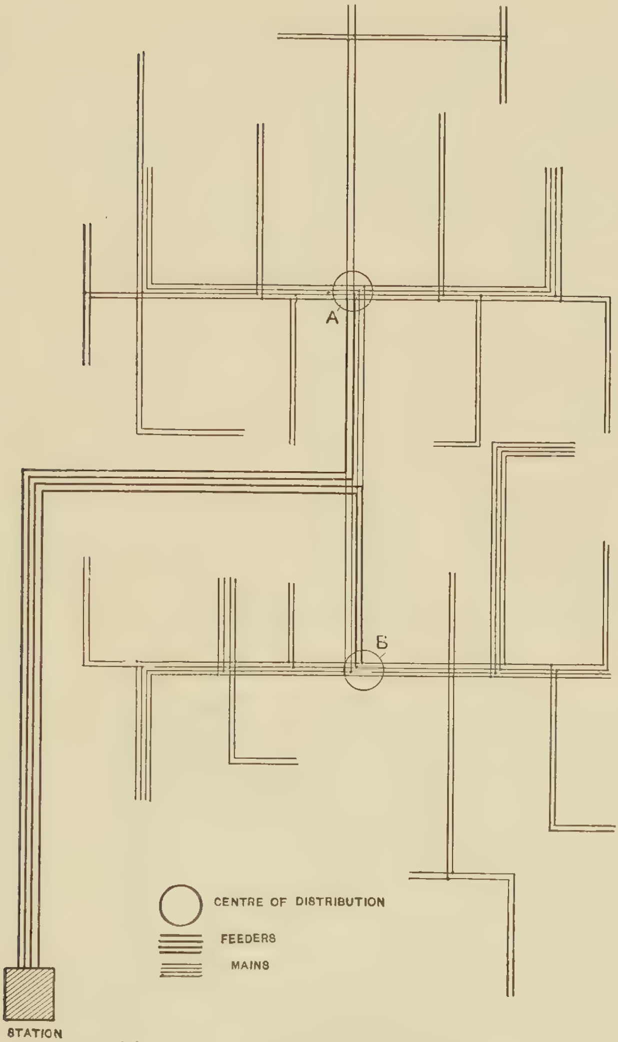


Fig. 12. Two-phase Four-wire Feeder.

One method of arrangement of a four-wire two-phase feeder supplying a mixed light and power load is shown in Fig. 12.

Where two terminals of a two-phase generator are connected together, as shown in Fig. 13, two of the four wires may be combined in one neutral wire and the feeder and main system reduced to a three-wire basis.

The neutral wire in such a system carries the resultant of the current in the two phases, which is 41.4 per cent more than that in the phase wires. That is, in a feeder carrying

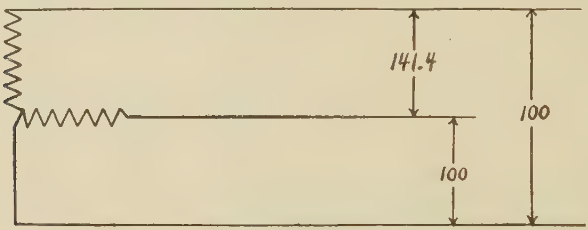


Fig. 13. Three-wire Two-phase System.

100 amperes on each phase wire the neutral wire carries 141.4 amperes. If the same size of wire is used on each pole of the circuit, the energy loss is the same as it is in a four-wire two-phase feeder under the same conditions. There being but three wires it is evident that only 75 per cent as much copper is required for the three-wire feeder as for a four-wire two-phase system under equivalent conditions.

In cases where feeders are so short that they are loaded up to the current carrying capacity of the wires, it is desirable to use a larger conductor on the neutral. In such cases the saving in copper is not more than 10 to 15 per cent.

In the primary distributing mains where, for mechanical reasons, no wire smaller than No. 6 should be used, a saving of 25 per cent is generally realized.

In cases where the load density is high the advantage of saving in copper by using higher voltage has been realized by the use of a double two-phase circuit operating at 2200 volts from phase to neutral with 4400 volts between the phase wires,

as shown in Fig. 14. This arrangement permits the use of 2200-volt transformers and gives an increase of feeder capacity of 100 per cent by the addition of one conductor to a four-wire circuit or two conductors to a three-wire two-phase circuit.

The five-wire combination is used from the point of supply to the central part of the district served, and from the center of distribution the branches are carried as three-wire two-phase mains in the manner illustrated in Fig. 14.

This system increases the radius of distribution from a given point of supply and has been used to a limited extent where conditions were such as to make it economical.

With two-phase systems, it is usual to step up the voltage for any transmission of large amounts of energy by two transformers connected by the " Scott connection." (See Chapter VII.) This produces three-phase currents on the high voltage side, permitting the transmission to be made on the more economical three-phase system. The reverse arrangement is used at the remote end of the line when there is a light and power load to be distributed by two-phase currents.

Three-phase Systems. — Such systems are operated from generators having three sets of windings in their armatures, which are so placed that they deliver three equal voltage waves which are a third of a cycle apart. When these three windings are connected in series to form a closed ring the sum of the electromotive forces is always zero and no current flows in the ring, at no load.

When three wires are connected at the junctions between adjacent coils they constitute a three-wire three-phase circuit which is said to be delta connected. See Fig. 15 (*A*).

When the windings of the generator are so connected that the three corresponding terminals of the coils are joined together, as in Fig. 15 (*B*), the line wires are connected to the other three terminals and to the common or neutral point,

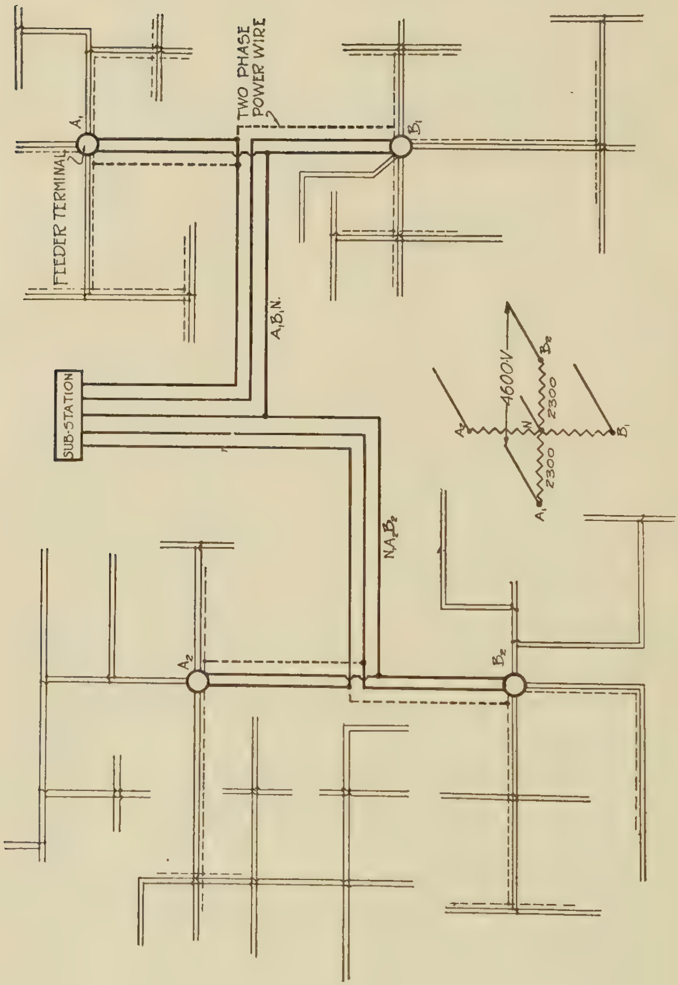


Fig. 14. Two-phase Five-wire Circuits.

making a four-wire circuit which is said to be Y or star connected. With a balanced load the fourth wire is not needed and a three-wire circuit may be used for motor loads even though it is supplied from a star connected source.

For general distribution purposes, the three-wire system is best adapted to use in the smaller cities where distances are

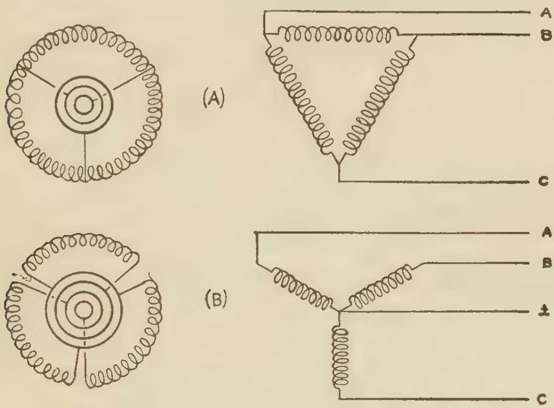


Fig. 15. Delta and Star Connections.

not greater than can be properly covered at 2200 volts and where feeder loads are under about 500 k.w.

The four-wire system is normally operated at 2300 volts from phase wire to neutral with 4000 volts between phase wires. This is more economical where the load is denser, feeder loads are heavier, and distances of transmission to outlying suburbs are greater, as is the case in the larger cities.

Three-wire distribution requires but three wires for the distributing mains while four wires are required in the four-wire system in places where power consumers requiring 25 horse-power and upward are served. Three wires are sufficient in either system for power installations under 25 horse-power as they can be served by two transformers in either case by the scheme of connections illustrated in Chapter VII. The

cost of the extra conductor in the four-wire main system may largely offset the saving in feeder copper except where feeders are more than two miles long or where the load is so dense that the feeders are numerous and the mains do not extend over a very large area.

This applies chiefly to districts where there is so general use of power that all phases must be carried on the majority of the streets. In residence districts where the load is chiefly single-phase, it is usual to use two-wire mains, balancing them on the three phases as nearly as is practicable. In some cities this has been carried to the feeder system by putting all lighting on one phase and running only a smaller third wire for such three-phase wire service as may happen to fall within the area served by the lighting feeder. This makes the lighting feeder virtually single-phase, and has the advantage that pressure regulation may be made somewhat simpler as only one regulator is required.

Where lighting is carried on each phase with potential regulators in each wire, the regulation of the pressure on the different phases is somewhat complicated when the load changes more rapidly on one phase than on the others.

This may be seen by reference to Fig. 16 showing the phase relation of current and pressure in a three-wire three-phase circuit. The lines AB, BC, and CA represent the line pressure. The lines AR, BS, and CT represent the resistance drop in the line wires with balanced load. AU and CV represent the drop in the A and C wires where the CA phase has twice as much load on it as the other two phases. The pressure coil of the regulator in the A wire is connected across the CA phase, and it therefore adds pressure to the C phase along the line AW. The regulator in the C wire, drawing pressure from the BC phase, adds pressure along the line CX. Thus both of these regulators affect the pressure between the C and A wires. With a change in load which occurs on one

phase, the regulators in both *C* and *A* wires must be operated to compensate for the additional drop in that phase. With hand regulation, close attention by the operator is required

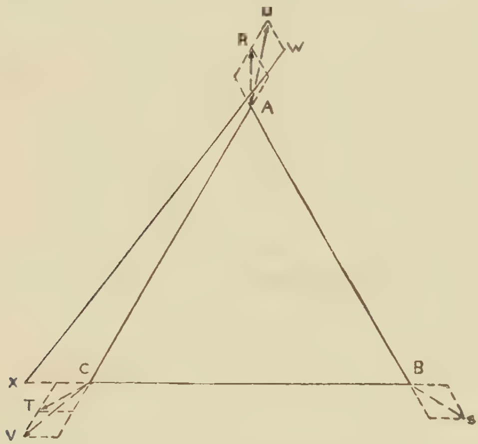


Fig. 16. Drop on Three-phase Circuit.

while the load is coming on in the evening. With automatic regulation and suitable compensating devices, however, this difficulty is not a serious one.

A typical arrangement of a three-wire three-phase feeder with single-phase branches in a portion of the district served is shown in Fig. 17.

A desirable method of operating this system in residence sections is to carry all the lighting on one phase of a feeder with a smaller third wire carried only to such points as require it for power users.

This plan permits the use of a single potential regulator on each lighting feeder, which permits of accurate regulation of pressure and reduces the disturbance due to power load to a minimum.

The *four-wire three-phase* system has several advantages over the three-wire system, and has been adopted in most

of the larger American cities which have remodeled their early equipment or developed new systems since the year 1900. The first large four-wire system was adopted for the outlying parts of Chicago in 1898, and that system is one of the largest of its kind in existence. A large suburban territory around

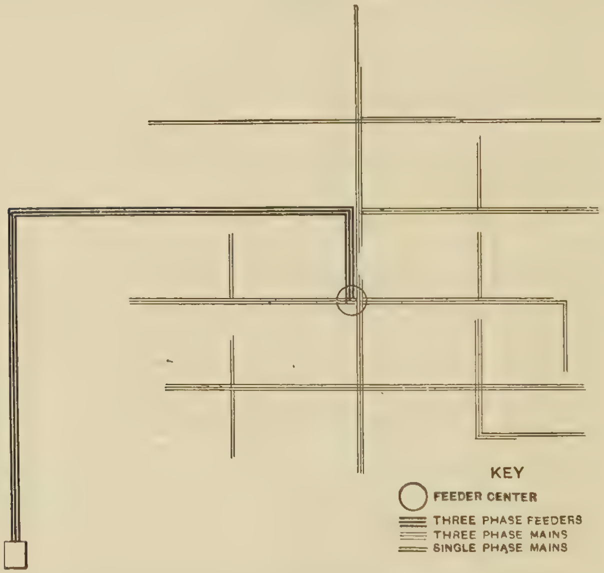


Fig. 17. Three-phase Three-wire Feeder.

Boston is served by the four-wire system, and it is in use in Cincinnati, Baltimore and many other smaller American cities.

The chief point of superiority in this system is that the transmission is effected at 3800 to 4000 volts, which increases the range of distribution to nearly twice that of the 2200-volt system. The pressure from either phase wire to neutral being 2200 volts, standard 2200-volt transformers are used for both light and power service.

The lighting branches are made single-phase as in other polyphase systems, but the importance of a careful balance of load on the feeder is reduced very greatly, as the neutral

wire carries the unbalanced current and it is quite feasible to regulate pressure on all phases satisfactorily regardless of balance. In fact, one method of developing a four-wire feeder system consists in starting with a regulator on but one phase, all lighting being on that phase. As more lighting load is added another phase is equipped with a regulator and finally the third regulator is added. Such a method is quite satisfactory when a line-drop compensator is installed in the neutral wire, as well as in the phase wire.

When the area to be served is so large that it is not possible to distribute all the lighting load of a four-wire feeder from one point without too much drop in the #6 primary main, some of the principal mains may be made larger, or the territory may be so divided that all lighting in one district is on one phase and that in the other districts on other phases. Two of the heavy feeder conductors are then run to the center of the lighting district, thus shortening the mains and permitting each phase to be regulated for the drop on the feeder and mains on that phase. Such an arrangement of a four-wire feeder is shown in Fig. 18.

The neutral wire in this system naturally runs near earth potential and is therefore usually grounded at the generating station. This makes it necessary to look after the insulation of lightning-arrester cases, cables at points where they join overhead wires, fuse boxes and other fittings somewhat more carefully than in other systems. It is also necessary to exercise more care in working on lines where there are two or more phases present, since the difference of potential between phases is about 3800 volts and that to ground is 2200 volts normally.

This system requires one-third the copper in the feeders which is required for a single- or two-phase system at 2200 volts, or 44.4 per cent of that required for a three-wire three-phase system at 2200 volts under equivalent conditions. This saving is somewhat offset by the increased cost

of four-wire mains as compared with two- or three-wire mains.

The smaller three-phase power users up to 25 horse-power may be supplied from two transformers with open delta-connected secondaries as in the three-wire system.

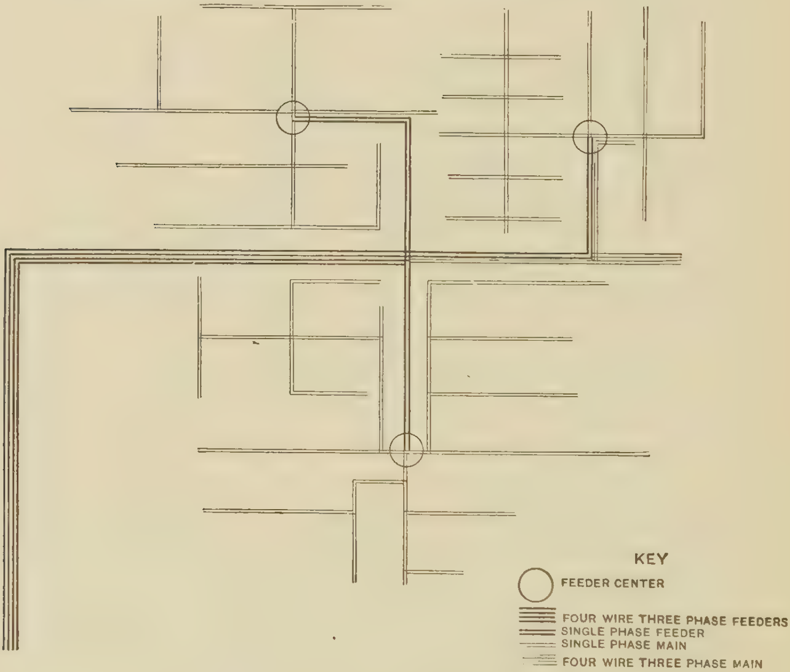


Fig. 18. Four-wire Three-phase Feeder.

The supply of power service in manufacturing districts is sometimes accomplished by the use of separate power feeders, the lighting being carried on other circuits. The use of separate power circuits tends to produce a duplicate distributing system and requires increased feeder capacity on account of the lower power factor, while with combined service, the lighting tends to keep the power factor up. The diversity of demand between power and lighting loads also

makes possible a considerable saving in feeder capacity where the lighting load in a given district is of the same order of magnitude as the power load.

Thus the policy of a combined feeder system is preferable from the standpoint of both feeder and main investment, in most cases.

With proper pressure regulating apparatus, there are not many situations where the lighting service cannot be made what it should be, when lighting and power are served from the same primary mains.

Copper Economy of Distribution Systems. — The comparative copper requirements of distribution systems of the various kinds before described, as they work out in practice, are of economic importance and may be illustrated by consideration of an assumed feeder taken to be representative of the average city.

The district served by an average feeder will usually (in polyphase systems) carry an appreciable percentage of power load. The length of a feeder to its center of distribution averages about 5000 feet and the length of distributing mains served by the feeder may be taken as 15,000 feet of single phase main for each of the phases. The polyphase power service will require additional phase wires in the system of mains which will be assumed to parallel the lighting mains for a distance of 5000 feet.

The length of wire required for the feeder and mains of such a circuit using the various systems is as follows:

	Feeder	Single Phase Mains	Power Mains	Total Mains
Single phase, 2-wire	10,000	30,000		30,000
Two phase, 3-wire	15,000	60,000	5,000	65,000
" " 4- "	20,000	60,000	10,000	70,000
" " 5- "	25,000	120,000	10,000	130,000
Three phase, 3-wire	15,000	90,000	5,000	95,000
" " 4- "	20,000	90,000	10,000	100,000

At the distance assumed, and at a voltage of 2300, the size of the feeder conductor is fixed by its current carrying capacity, since the line loss at the safe carrying capacity of the feeder cable is not so great as to require the use of a larger conductor to reduce it. Feeders are, therefore, usually made of some standard size fixed by the ability of the mains to deliver the energy without excessive drop in pressure from the center of distribution to the longest branches.

Assuming that the feeder capacity is 175 amperes at 2300 volts, that the load per phase is 400 kv-a. and that the size of mains is #6 A.W.G., the weight of conductors required for the various systems is as follows:

	Feeder, Cir. Mils	Weight of Copper, Lbs.					
		Kv-a.	Feeder	Per Kv-a.	Mains	Total	Per Kv-a.
Single phase, 2-wire	105,500	400	3188	7.97	2,379	5,567	13.92
Two " 3- "	105,500	800	3188	7.03	5,154	10,776	13.47
" " (neutral)	167,800	...	2434	....	....	....	....
" " 4-wire	105,500	800	6376	7.97	5,551	11,927	14.91
Three " 3- "	211,600	1200	9564	7.97	7,533	17,097	14.25
" " 4- "	105,500	1200	6376	5.31	7,930	14,306	11.92
Quarter " 5- "	105,500	1600	7970	4.98	10,308	18,278	11.42

The four-wire three-phase and five-wire two-phase systems being operated at 2300 volts to neutral with a pressure of about 4000 volts between phases are, for this reason, the most economical in their use of copper. In the feeder conductors they require about 5 lbs. of copper per kv-a. under the condition assumed as compared with 7 to 8 lbs. per kv-a. for the other systems. The copper requirements for the mains are about 6 lbs. per kv-a. for all the systems, the two- and three-wire systems having a slight advantage in this respect because of the extra phase wires required for power service.

The four- and five-wire systems have a further advantage that the losses in these systems are only about half those of the other systems. If the copper in the feeder conductors of each of these systems is so designed that the percentage of loss and the load is the same in each the copper per kv-a. required for feeders and mains in the various systems is as follows:

	Lbs. Copper per Kv-a.		
	Feeders	Mains	Total
Single phase	15.94	5.95	21.89
Two phase, 3-wire	11.95	6.44	18.39
" " 4- "	15.94	6.94	22.88
Three " 3- "	11.95	6.28	18.23
" " 4- "	5.31	6.61	11.92
Quarter" 5- "	4.98	6.44	11.42

In actual practice the shorter feeders are laid out on the basis of current carrying capacity while the longer ones are so loaded as to keep the pressure regulation within practicable limits and therefore are loaded more nearly on the basis of the second of the foregoing tables.

The actual figures of copper per kv-a. of course apply only to the conductors assumed for illustration, viz., feeders 5000 feet long and a total length in mains of 15,000 feet. In cases where the load is very dense the total use of copper tends to approach the condition illustrated by the columns showing the requirements for feeders. With very scattered load the length of mains may be greater than three times the length of the feeders and the values of copper in the mains will be correspondingly increased.

Under such conditions the 4000-volt systems have the advantage of being able to distribute scattered load over greater distances without excessive drop in pressure in the mains. This tends to require a lesser number of feeders for a given district.

Arrangement of Primary Mains. — The primary main system cannot be interconnected as are the mains in a low-tension system, because it is impracticable to provide fuse protection which will isolate a section of main which is in trouble without simultaneously blowing other fuses through which the energy is supplied. Thus the primary system loses the advantage of parallel feeding, and the feeder end must be located as nearly as possible to the electrical center of the district which it serves, thus forming a center of distribution with radial mains. These centers of distribution should be chosen so that the drop on the primary main will average about 2 per cent from feeder end to transformers. This limit is not always commercially feasible, however, in the case of lines to outlying districts.

The center of distribution plan of arranging primary mains is quite commonly used in the larger systems. In this plan the feeder is terminated at a point near the electrical center of the district which it serves, and branches are radiated in as many directions from this point as there are routes available,

usually 3 to 4. In this manner the mains supplying service nearer the source are given the same pressure regulation as others which are served by the feeder under similar conditions of load and distance from the center.

By this plan the pressure may be regulated to maintain the correct value at the center of distribution at all loads and the range of pressure variation between no load and full load is a minimum.

In business or manufacturing districts where the length of mains is short it is sometimes possible to take off the few taps required at the nearest point available, making a "tree" system such as that shown in Fig. 19.


Fig. 19. Tree System.

This is also used on the radials from a center of distribution and is an economical arrangement where the pressure drop between the nearest and farthest taps is within permissible limits. This is a condition found where distances are short or load density is very light.

In three-phase, four-wire systems a modified form of the center of distribution plan may be used, as shown in Fig. 18. The center of distribution of each phase is located with reference to the electrical center of the single-phase load carried by that phase. Since each phase can be regulated for pressure separately, this gives a good distribution in scattered districts, and permits feeders to be loaded more heavily than is possible when the load is distributed from a single center. In the denser business districts it is possible to pick up enough load for a feeder within a small radius, and a single center is adequate.

The separate centers of distribution can be used in two-phase systems but do not work out well for three-wire, three-

phase circuits, since the line drop compensators cannot be set to take care of drop in the single-phase branch after it leaves the other places.

Emergency Switching Points. — One of the chief operating advantages of the center of distribution plan of arranging a feeder is that, in an emergency, the principal mains having the center of distribution may be equipped with suitable disconnecting devices by which they may be cut off with a minimum of time spent in travel. With each principal main thus equipped, the repair man may readily determine which branch of the circuit is in trouble.

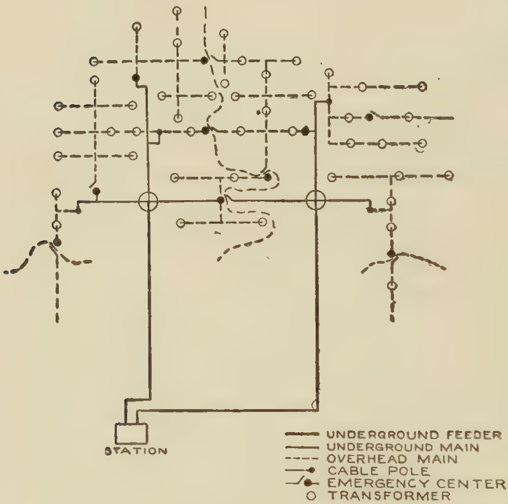


Fig. 20. Emergency Disconnectives.

Where portions of the primary system are underground and where mains of adjacent feeders come together, it is important that there be suitable facilities by which the mains of the two circuits may be joined together in emergencies. Cable repairs require a considerable time and emergency connections must be provided in sufficient number to permit the minimum interruption of service. Emergency switching points are also necessary as a means of putting sections of cable out of service while new cable taps are being cut in. The safety of linemen and continuity of service largely depend upon the

facility with which sections of the primary main system may be controlled.

An arrangement of two adjacent feeders with mixed underground and overhead lines provided with facilities for emergency switching appears in Fig. 20. This is arranged so that in case of the failure of any section of cable main, the service may be resumed as soon as the potheads on the cable poles connected to the main can be opened and the emergency connection between the overhead branches of the adjoining circuit closed.

Direct-current Systems. — Direct-current systems are two-wire at 550 volts, or three-wire at 110–220 or 220–440 volts. Two-wire, 550-volt power systems, which were established before polyphase systems were available, still survive in some American cities, partly because the general distribution is carried out by alternating current and partly because it would be a matter of much expense to abandon the system and exchange all the direct-current motors for others suited to the alternating-current system.

This voltage is high enough to permit economical distribution in medium-sized cities and the savings to be effected by a change are chiefly those incidental to the elimination of a separate set of lines paralleling the main lighting system.

Direct current at 220–440 volts on the three-wire system is distributed in a few medium-sized American cities. The saving in copper over a 110–220-volt, three-wire system hardly compensates for the loss in adaptability to high-efficiency lamps, fans, heating appliances and similar devices.

The three-wire system at 110–220 volts (approximate) is the one in most general use. The Edison systems established in the large American cities between 1882 and 1890 are for the most part still continued in the central portions of those cities, their growth having followed the development of the commercial and manufacturing interests very closely. In

the larger cities the direct current is now derived chiefly from synchronous converters, the direct-current generating machinery having been replaced by more modern alternating-current units or held in reserve for use during the maximum-load period of the winter months.

The scattered mains originally laid have grown to heavy networks with feeders supplying them at frequent intervals and service connections into almost every building.

The direct-current system is maintained for the most important service because of the demand for variable-speed motors above referred to, and because of the availability of the storage battery as a reserve.

With storage batteries located at important points on the system, the interruption of service to a converter substation may occur with little or no interruption to the direct-current service. In case of a general interruption affecting several substations partial service may be maintained for a sufficient time to permit converters to be synchronized and gotten into operation again. There are several large direct-current networks in America which have not suffered a general shutdown during ten years or more.

The mains from which service is taken in the underground portions of direct-current networks are rarely smaller than #0 or larger than 1,000,000 cm. In the heavily loaded districts 350,000 to 750,000 mains are commonly found. The feeders vary from 4/0 to 2,000,000 cm. The common sizes in the denser parts are 750,000 to 1,500,000 cm. The network is joined at street intersections through fused junction boxes. The main in each block, therefore, has a double feed, which enables it to carry a heavy load at any point more satisfactorily than if there were no network arrangement. This also assists in maintaining continuous service, as the melting of a fuse at either end may merely drop the pressure without blowing the fuse at the other end. In case of a

burnout of a main the fuses at both ends are usually blown, thus isolating the section and preventing the extension of the trouble to other blocks.

Combination of Systems. — A combination of alternating with direct current, or of two alternating systems, at different frequencies is usually found in the larger cities.

Direct-current systems are supplied by converting from alternating current, in many cases, and 60-cycle systems are supplied in part from a 25-cycle source of energy.

The combination of alternating-current transmission with direct-current distribution was initiated at about the time when 60 cycles was being made the standard frequency for alternating-current distribution. This frequency was, however, too high to permit satisfactory operation of synchronous converters as then developed. The efficiency of the converter was, however, materially better than that of the motor generator, which was the alternative means of conversion. In the systems where direct-current distribution largely predominated, the frequency was, therefore, made 25 cycles to permit the use of converters.

This, in turn, necessitated the use of motor generator sets known as "frequency changers," to supply that part of the system in which alternating current was distributed, the use of 25 cycles for this service being unsatisfactory.

With the introduction of the interpole converter, the performance of these machines was so improved as to permit their use at 60 cycles, and the further development of 25-cycle systems was greatly retarded. The frequency changers were retained as a connecting link to be used for transfer of load from one generating system to the other, but little additional capacity has been provided, since the frequency of 60 cycles has been generally accepted as standard for America.

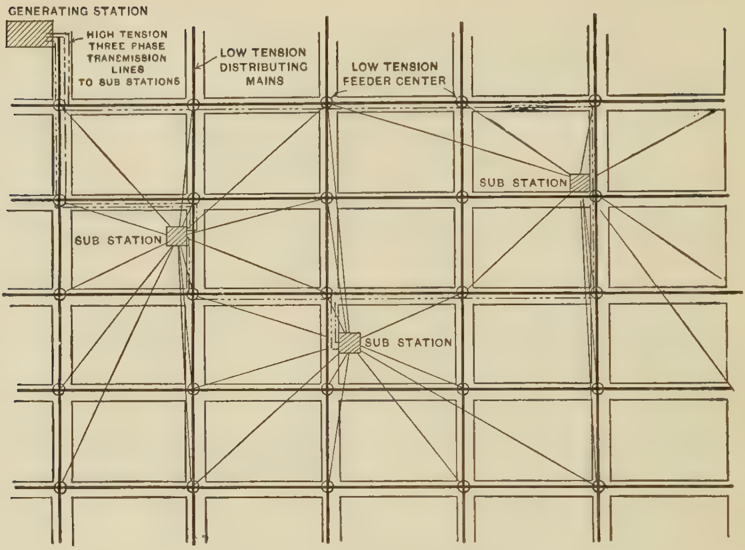


Fig. 21. Low Tension Network.

A combination system, including alternating-current supply and direct-current network, is illustrated in Fig. 21. The feeders of the direct-current system are shown diagrammatically.

CHAPTER II

URBAN TRANSMISSION SYSTEMS

Classes of Transmission Lines. — The transmission of energy in large quantities is necessitated by three general conditions: (*a*) the presence of water power at a point remote from the power market; (*b*) the presence of a group of distributing substations in a large center of population and (*c*) the existence of a group of towns and cities separated by distances greater than those separating city substations but yet within economical reach of a central point at which a power station may be located.

The transmission of energy in very large amounts is involved where a source of hydro-electric energy is located at a considerable distance from the power market, or where energy is exchanged between neighboring utilities forming a part of a " super-power " transmission system.

In such cases the lines are operated at voltages above 100,000 because of the distances involved and the amount of energy which must be transferred, voltages above 200,000 being used where distances exceed 200 miles.

The design of such systems involves many special problems which cannot be adequately treated within the scope of this chapter.

The second case, that of urban transmission cables connecting a group of substations in a densely populated district, is one common to all larger cities and will be considered in detail.

The third condition, that of district supply, is one which is being rapidly extended and is of great importance to the development of industry and agriculture.

Where circuits operated at transmission voltages are used to supply energy to the towns and villages of one or more counties, the distances are such that the circuit is necessarily operated at a transmission line voltage though the load in many of the towns is no greater than would be served from an ordinary distribution circuit if it were taken by an individual consumer in a city distributing system. Such a transmission line is thus really a high voltage distribution circuit. On the other hand, there is a class of large industrial users of energy in the cities whose individual demands are so great that they require an excessive amount of circuit and substation equipment when supplied from a distribution system. When such users have a demand of 500 kilowatts or more the supply is best provided by lines from the transmission system with a transformer vault or substation on the user's premises.

Thus the distinction between transmission and distribution is relative and it is apparent that when the load is large or the distance great, the transmission system may include some distribution lines.

Voltage. — In general, the voltage selected for a transmission system should be such that energy can be delivered without excessive loss at the most remote parts of the territory supplied. The "rule of thumb" of 1000 volts per mile, which is often used as a guide, is based upon the fact that at this voltage, with copper conductors, a current density of one ampere per 1000 circular mils gives a loss of about 10 per cent. Thus the line carries approximately its rated safe current at a loss of 10 per cent. In the case of the very large cities where lines are called upon to carry 5000 to 10,000 kw. or more, to a single substation, this rule gives voltages which are too low for the most economical investment in cable.

In many cities the lower voltages used in the years when

load units were smaller have been supplemented by such pressures as 13,000, 22,000, and 33,000 for distances of 5, 10, and 20 miles respectively. Lines are made as large as cable ducts will permit and have capacities at the above voltages of 8,000 12,000, and 15,000 kv-a. respectively. The higher of these voltages are employed for the connecting lines between large generating stations in different parts of a large city and for the underground connection to a step-up transformer station at the edge of the city from which energy is sent to or received from a neighboring station or system.

In the larger metropolitan districts line capacities of 30,000 to 50,000 kv-a. are provided for such interchanges of energy in some cases.

The upper limit for urban transmission which is largely underground is fixed by the limitations of cable manufacture. The upper limit of three-conductor cables in American practice has been reached at 33,000 volts. However, progress made by manufacturers abroad indicates that further advances will be made. With single-conductor cables the limit is not so well defined. Installations at 45,000 and 66,000 volts have been made successfully and the development of methods which will permit the use of voltages of 100,000 to 150,000 is proceeding. Such cable eliminates the necessity of transformer stations at the edge of the city and permits the use of a single step-up transformation at the power station.

On the other hand, with district supply systems spreading over wide areas in which load densities are very light, the adoption of voltages less than 1000 volts per mile is sometimes possible. These lines are chiefly overhead and are operated at 33,000 or 44,000 volts (nominal). At these pressures, cities and towns with loads of 50 to 500 kw. may be carried at distances of 30 to 100 miles with reasonably satisfactory regulation and losses. As the load densities increase, the

number of points of supply is apt to be increased, thus shortening the average distance of transmission as may be necessary.

Standard voltages should be selected for new installations, in order that advantage may be taken of machinery and apparatus already developed for these voltages, as far as possible.

Line Capacities. — A large proportion of the lines making up bulk supply systems in large cities are placed underground in lead-sheathed three-conductor cables drawn into ducts. The most economical use of capital is made when such cables are as large as can be properly handled. The kilowatt capacity of a high-tension cable at a given voltage increases more rapidly with increasing sizes of copper, than the cost of the cable. The most economical cost per kilowatt, therefore, requires the use of as large a cable as it is practicable to draw into a standard duct.

The capacity and maximum size of three-conductor cables which can be drawn into a $3\frac{1}{2}$-inch duct are as follows:

Voltage	Type of conductor	Circular Mils per cond.	Amperes per cond.	Kv-a. capacity
13,000	circular	300,000	250	5,600
13,000	sector	500,000	360	8,000
22,000	circular	250,000	220	8,400
22,000	sector	400,000	300	11,400
33,000	sector	350,000	270	15,400

The terms "circular" and "sector" used to describe the type of conductor refer respectively to the ordinary conductor having a circular cross section and to a specially shaped cross section similar to the sector of circle by which more copper

can be put into the conductor without increasing the outside diameter of the cable.

The current values are taken for average conditions. They are somewhat high for situations where the facilities for heat radiation are poor, or where there is a considerable number of other cables liberating heat in the same duct line. These amounts of power could be exceeded for a few hours during a peak load, without risk of injury, in many cases.

The carrying capacity of overhead lines of the same size and at the same voltage is about 33 per cent greater than that of underground cables as given above. At 33,000 volts, the capacity of a line of 0000 A.W.G. wire is approximately 13,000 kv-a.

These loads are based on the carrying capacity of the conductor, and neglect distance. If the distance approaches or exceeds one mile per 1000 volts of line pressure, these capacities will give losses in excess of 10 per cent. They are therefore of interest for lines which are well within the distance at which drop in pressure is a factor, and as indicating what can be done in the way of loading lines in an emergency, where temporary overloading and excessive drop may be preferable to an interruption of a portion of the service.

Frequency. — In America the standardization of a frequency of 60 cycles per second for transmission as well as distribution is steadily progressing. The 25, 30, and 50 cycle frequencies established in earlier years for special reasons are not being adopted for new undertakings. Where 25 and 60 cycle systems are under the same management there is a tendency to make all additions to the generating plant at 60 cycles with the intention of ultimately abandoning the 25 cycle equipment.

The use of 125 and 133 cycles which was common in the early alternating current systems was found too high for

satisfactory pressure regulation with motor and arc lamp service, and 60 cycle systems were introduced at about the same time that 25 cycle transmission began to be introduced as an auxiliary method of distribution in direct current systems.

Arrangement of Lines. — The scheme of connections employed in urban transmission varies with the size of the units of load delivered at various points and to some extent with the requirements of the users of the service.

In the larger cities where the number of large individual users is considerable and the size of distribution substations is from 2000 to 15,000 kw. or more, the lines are carried in cables underground. It being most economical in cost per kv-a. of capacity to employ as large a cable size as is practicable, the arrangement of line connections becomes a problem of adapting a cable unit of 4000 to 8000 kv-a. to a group of load units of 500 to 15,000 kv-a. or more.

The service rendered usually requires that there be provided an adequate reserve supply for use in case of the failure of any of the cables upon which dependence is placed for the normal supply.

The reserve cable is brought from the nearest source of supply where spare capacity is available. In some cases this is a duplicate line from the main source of supply, but more often it is a loop from a tie line or from a ring circuit or a tap from a different line. For distributing substations one direct line may serve for as many as three substations through tie line cables, thus reducing the percentage of reserve capacity very materially.

Lines run directly from a source of supply to a point of distribution are known as radial lines since they form radials from a central source in a diagrammatic representation of the line connections of such a system.

Radial lines are used where there are but a few points of distribution which lie in the same general direction from the source of supply. If some of these are relatively small, they may be supplied by a tap from a radial line or by two taps from different lines.

When the load density has reached a point where there are more than three points of distribution in the same general direction from the source of supply and the total load of the group is within the capacity of one cable, the *ring* system of connections is most economical.

With a ring system each point is supplied by looping the ring so that in case of the failure of any section of the cable forming the ring, the switches at each end of the faulty section can be opened and service continued from the other side of the loop. This, of course, requires the use of an oil switch on each side of the loop at each point of distribution.

The opening of switches at each end of a faulty section is sometimes made automatic, so that a section of cable may fail without interrupting service.

It is apparent that in case of the failures of the section of cable on either side of the ring which forms the connection to the source of supply, the corresponding section on the other side of the ring will carry the load of all the points supplied by it. Thus the amount of load which may be carried on the ring is limited to the capacity of the cable on either side.

When the load has exceeded the capacity of the ring cable it is necessary to add a radial line to take off the largest of the units of load, or if these are chiefly small in size but rather numerous, it may be preferable to create a second ring.

Radial lines are usually required where the load of a distributing substation exceeds the capacity of the size of cable which is standardized for such work.

In the larger cities the range of load units is such that it has been found desirable to have two standards of line capac-

ity, one of 3500 to 5000 kv-a. and another of 7000 to 9000 kv-a. The smaller unit is used for groups of industrial users having loads of 500 to 1500 kv-a. and for distributing substations at new locations. The larger size is used for substations having loads of 7500 kv-a. or more.

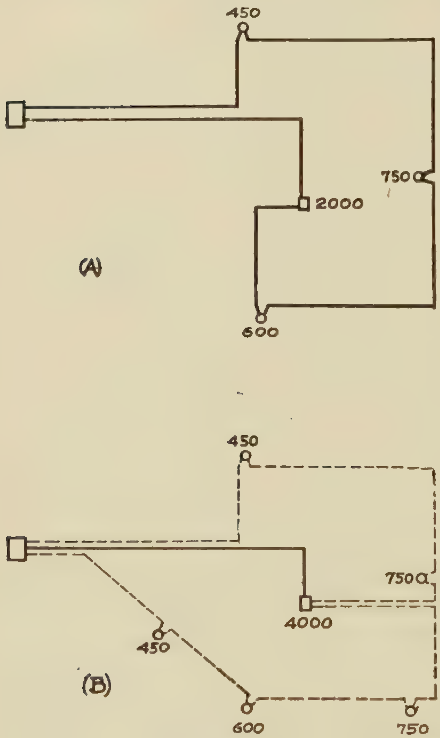


Fig. 22. Development of Network.

Illustration.— These general principles may be made clearer by the assumption of specific situations which are similar to those found in the larger cities.

The group of units of load in Fig. 22 (*A*) includes three industrial consumers having an aggregate load of 1800 kv-a. and a distributing substation with 2000 kv-a. and are served by a ring made up of 4000 kv-a. cable, which provides ample reserve under the most severe condition, i.e., with one of the sources of supply cut off.

After the substation has grown to 4000 kv-a. and there have come to be five industrial consumers demanding 3300 kv-a. the line may be economically arranged as in Fig. 22 (*B*).

A 4000 kv-a. radial line has been run directly to the substation and the ring has been extended to take on the two additional users. With this condition the failure of either

of the three lines leaving the source of supply throws the entire load of 7300 kv-a. to the other two lines. As it is not probable that the two remaining lines will divide their load proportionately because of the differences in length it is sometimes necessary to reinforce the capacity of the group some time before the total load has reached the full capacity of two of the three cables.

The condition sometimes found in an industrial section of a large city is shown in Fig. 23. In this section there are five

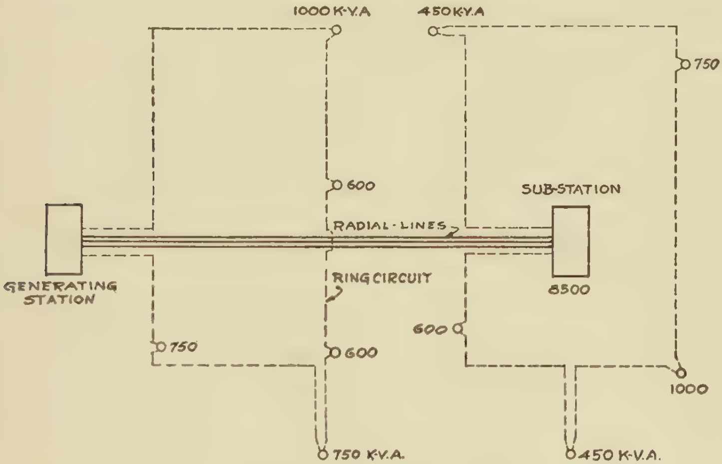


Fig. 23. Bulk Supply Network.

large users served from a ring circuit supplied directly from the source. These, being nearer the source than any distributing substation, are most advantageously supplied by a direct ring. The five industrial users who are located farther away than the distributing substation have a load of 3450 kv-a. which is carried from the bus of the distributing substation for this district.

This substation has 8500 kv-a. of general load and this gives the radial lines supplying it a total load of 11,950 kv-a. This

would require four lines of 4000 kv-a. capacity (one being a reserve line) or two lines of 8000 kv-a. and one of 4000 kv-a. capacity. As the load becomes larger the 4000 kv-a. line would be replaced by one of 8000 kv-a., increasing the capacity to 16,000 kv-a. for the group. Fortunately, the cost of cable does not increase in direct proportion to the cross-section of the copper conductors and the use of larger cables is therefore economical even though there may be a rather high percentage of reserve capacity at first.

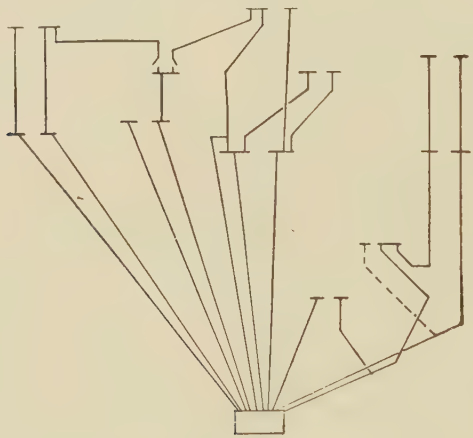


Fig. 24. Tandem Arrangement.

In the development of a bulk supply system of lines there are frequently situations where it is expedient to resort to various combinations of radials, tap connections, rings and inter-substation tie lines.

For instance it may be desirable to loop a tie line between substations to supply one or more industrial consumers, or a single customer may be so far to one side of the general system that a tap connection is resorted to as a temporary expedient until the customer's demand may warrant a greater line investment.

Where there is a series of substations for suburban towns, or for industries along a railroad route, the plan of using two radial lines along the same route and looping both of the lines into each point of delivery making a tandem arrangement, such as that in Fig. 24 has been found advantageous. In such cases the relays are arranged so that the failure of either line at any point cuts off only that part of the load which lies beyond the damaged section.

Bulk Supply Network. — With the multiplication of points of delivery a large system tends to become a network of inter-connected substations and large users. As in the case of distribution networks the problem of reserve supply is diminished materially as the completeness of the network is realized.

The line extension investment required to take on additional consumers is reduced and it is possible to load the main lines from the source of supply more nearly up to their rated capacity, thus reducing the investment held for reserve capacity. The problem of relay control by which damaged sections are automatically cut out is however made more difficult since the increased number of paths by which energy may flow to a cable fault increases the probability that relays will be operated at points where no fault has occurred, and the interruption of service is wider in extent than it should be.

In American practice this has resulted in the limitation of the number of lines inter-connected to groups of four to six direct lines, with their inter-connectors.

The protection of a network is most nearly approximated by the use of pilot wires and differential relays by which a cable failure operates the circuit breakers at each end of a ring section, but does not normally affect other section breakers.

Such a system has been applied to a large industrial power system in England quite successfully and has found useful application in parts of some of the larger systems in America.

In large systems (over 100,000 kw.) the amount of power available to flow into a short circuit is such that protective reactors are usually required in the outgoing lines, at the point of supply, to protect both generating equipment and oil circuit breakers from an excessive rush of power.

The effectiveness of such reactors is diminished as more lines are connected into a network and this tends also to limit the extent of a transmission cable network.

As the loads increase and more radial lines are required, the importance of having a diversity of routes to guard against

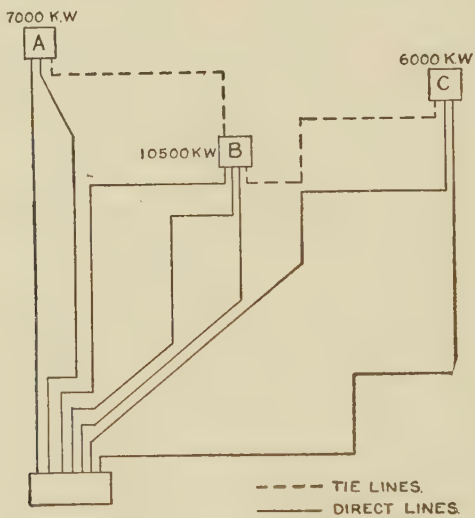


Fig. 25. Diversity of Routes.

the failure of two or more cables to the same substation increases. This condition is illustrated in Fig. 25.

Interurban Transmission Systems. — The transmission of energy from a central source to cities, towns, and rural communities has taken a large place in the economic development of American civilization.

The greater economy of large power stations has made it undesirable to continue to operate smaller power stations in towns and villages and these have been replaced by transmission lines supplied from a larger source of low cost energy. With the construction of such lines a supply of energy to many villages and smaller towns which had before had no electric service became possible and the use of highways also created a market for electric service from the farmers along the route.

The power requirements of these groups are progressively smaller and the points of use more widely separated as the distributing lines are extended farther from the centers of population. The problem of providing for a system of supply which is commercially practicable requires careful selection of equipment and has resulted in the development of three classes of lines.

(*a*) Lines of large capacity and high voltage used strictly as transmission lines without intermediate tap connections. These lines are commonly operated at pressures of 33,000 to 150,000 volts and carry loads of 5000 kilowatts to 50,000 kilowatts or more. Such lines are necessary as a means of transferring large blocks of power from a low cost source of energy to cities and industries where it is used in large amounts and where the existing less efficient generating stations can be shut down for a considerable part of the time, thus effecting economy of operation. These lines are also of use in forming interconnections with neighboring power systems for the purpose of interchanging energy from time to time as the conditions of operation in the two systems may permit, thus forming what has been termed a " super-power " system.

At 33,000 volts these lines are carried on wooden poles in most cases, two circuits often being carried on the same pole line. At voltages above 50,000 the use of the suspension type of insulators and the larger capacity of the circuits tends to the adoption of steel tower lines on private rights-of-

way. These are designed to carry two circuits where necessary, the conductors being carried preferably in a vertical plane, with the middle conductor slightly to one side to prevent short circuit when sleet causes unequal sags in the conductors.

The expense of transformers, switches and other substation equipment for higher voltages is so great that it is not desirable to make tap connections except for large amounts of load (3000 kilowatts or more), and such lines are usually carried only to the more important load centers.

(*b*) Lines of medium capacity and voltage which deliver energy to cities and towns along the route. Junctions with other lines of the same class are formed at certain points by which a reserve supply is available in emergencies.

These lines are those most largely used in the supply of energy to points requiring it in amounts of 25 to 2500 kilowatts. Such lines serve all the towns near which they pass and are usually carried on highways or on a right-of-way paralleling a railroad, thus reaching all the towns through which the railroad passes.

The voltages used for such lines are chosen in accordance with the load and distance, the larger part being at 13,200 or at 33,000 volts. The voltage is reduced to one suitable for local distribution at each town served from the line by a transformer substation of a type suited to the service requirements. The smaller towns are served by an outdoor installation of a single-phase transformer, there being no power large enough to require three-phase service.

(*c*) Lines of small capacity and voltage which distribute energy to villages, isolated industrial plants, and rural communities. These smaller lines are in reality purely distribution circuits which, because of greater distances than are usual in cities and towns, must be operated at voltages above 5000.

Such circuits are operated at 6600 volts in many cases where only lighting and small power are required.

Where there is a demand for power for manufacturing purposes or for such isolated industries as gravel pits, quarries, and the like, these lines are designed for three-phase service and may be 6600 volts three-wire, 4600–8000 volts four-wire or 6900–11,000 volts four-wire.

The use of 4600–8000 volt circuits is found chiefly in rural communities near the larger cities where the farms are subdivided into smaller units and each farm requires power for various purposes. The villages are supplied from the same lines. The principal advantage of this system is the ability to provide pressure regulation on the phases independently in accordance with their length. Single-phase taps at 4600 volts are carried when only lighting and small power are required.

In the Pacific coast states where power is required for each ranch in considerable amounts, it is found necessary to use 6900–11,000 volts for this class of service. This, of course, increases the radius of distribution and makes it possible to take larger loads in the circuits.

Distribution transformers for 4600 volt service are available in all the usual small sizes, and for 6600 volts in sizes from 3 kilowatts up. The cost of transformers increases as the voltage becomes higher and this relation may be seen in a relative way in the following ratios based on the cost of 2200 volt transformers as 1.

Capacity kv-a.	Relative Cost		
	4400 volts	6600 volts	11,000 volts
3	1.25	1.5	....
5	1.18	1.37	2.0
15	1.11	1.22	1.52

Control Equipment. — The problems arising in connection with high tension distribution of this kind involve the questions of disconnective switches, out-door substations, fuses, lightning arresters and potential regulators which are not usually a part of a straight away transmission problem.

The use of disconnective switches is necessary at junction points where branches must be opened at times to facilitate location of trouble or to shift load from one point of supply to another. These are commonly open air switches mounted on poles and operated from a point below by means of levers, as shown in Fig. 26.

Where the loads carried are small as compared with the line capacity, or where the distances are short as compared with the voltage, as is the case in certain stages of development, the line drop is likely to be within 5 per cent and it is possible to serve the wholesale users on the line without potential regulators at the receiving substations.

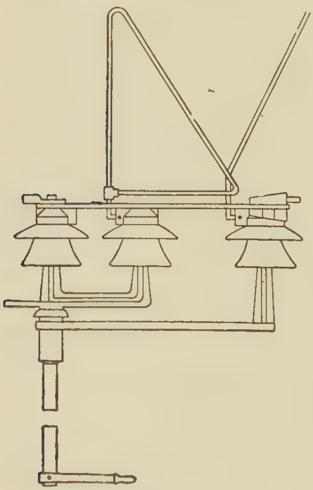


Fig. 26.

With the use of pole-type automatic regulators, however, it is possible to provide pressure control for a town or industrial user without the expense of an attendant. This is quite important for certain classes of service which require better regulation than is afforded by the transmission line and station bus pressure control.

Where the town was large enough to have had a generating plant before it was taken over on the transmission system, a building is usually available and regulating equipment of the inside type is used. Where no building is available, all

equipment is placed out of doors, since in many cases it is not necessary to house the equipment.

In the case of a factory, stone quarry, irrigation pumping plant or other industrial consumer, the equipment of transformers is mounted on poles or on a platform supported by poles, at a convenient point on or very near the consumers' premises. The equipment is usually provided with primary fuses, air break switches, and lightning arresters. In the case of a town, the transformers usually work from the transmission voltage to a voltage of 2200, the distributing line being operated in the usual way about town.

The transformers must be protected from the effects of discharges of lightning in some manner in these substations. Where there is a building and an equipment of 150 kw. or more, the protection may be secured by the use of oxide film arresters of a type suited to the line voltage. This equipment is too expensive, however, for smaller installations and, for these, horn gap arresters have been used to a considerable extent, the ground connection being provided with resistance sufficient to prevent an excessive flow of the line current to ground.

An out-of-door installation of this type is illustrated in Fig. 27.

The class of construction of lateral branches to towns or wholesale users from the transmission system, is determined by the importance of the load served and by the importance of the line from which the branch is taken. The cost of the extension should be kept within reasonable limits in view of the income to be derived and yet must not be of so low a grade as to jeopardize the continuity of service on the important main line.

In the case of small towns the loads are often less than 50 kw. and the 10 or 15 miles of line required may be constructed of iron wire on 25 or 30 foot poles in order to keep the invest-

ment per kw. within profitable limits. It is not unusual in running lines to growing communities to make an investment which is not profitable at first. As the community grows

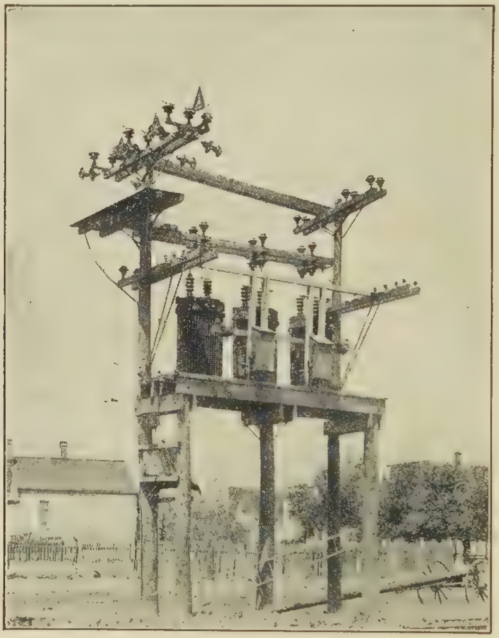


Fig. 27. Outdoor Substation.

and overloads the line it is replaced by a better grade of construction.

Constant Current Transmission. — The use of constant current has been limited to street lighting systems almost entirely in America. In France, however, M. Thury has developed a system of generators and accessories which are being used to transmit energy over considerable distance at constant current strengths of 100 to 150 amperes, at 20,000 to 30,000 volts or more.

In these systems the power is delivered to the line from the generators connected in series at voltages as high as 10,000 volts each, and is received by series motors driving alternating current generators which supply the distributing system. The generating and substation machinery is necessarily more complicated and expensive than that required for an alternating current constant potential system, but the high tension switching equipment is very simple.

The simplicity of the switching equipment results in a material saving in space, which is said to largely offset the differences between the cost of the motor-generator equipment and the step down transformer equipment which would be used with an alternating current transmission system at equivalent transmission pressures.

The use of direct current in the series transmission system makes possible the use of somewhat less insulating material in the cable system for a given working voltage, as the maximum pressure at the peak of the wave is 40 per cent higher than it is in a direct current system at the same effective pressure. The weight of copper required for a series system working at the same effective pressure and percentage of loss as a three-phase system is 33 per cent greater, since the three-phase circuit requires but 75 per cent as much copper as an equivalent single phase or direct current circuit. But by increasing the pressure in the series direct current system 33 per cent, the total weight of copper and thickness of insulation may be made the same as for an equivalent three-phase circuit. The series circuit has the further advantage that there are but two conductors to insulate as against three in the three-phase circuit.

Series transmission is obviously not so well suited to conditions where it is desirable to take off branches for industrial power consumers or for smaller towns, as is alternating transmission.

CHAPTER III

SUBSTATIONS

Establishment of Substations. — In the development of a city distributing system, the radius of action from the point of supply tends to increase as the population grows. After a time the number of feeders to certain districts remote from the generating station becomes such that the transmission may be effected at higher voltage to much better advantage. Such transmission involves transforming and regulating apparatus at a point remote from the generating station, which in turn requires a building and other accessories, and the result is a substation. The substation involves an investment in real estate (or a rental charge), transforming apparatus, switchboard, etc., and an operating expense for attendance and repairs. On the other hand the feeders running into the district to be served by the substation occupy valuable duct or pole space and require a large investment in conductors.

It therefore becomes profitable to establish a substation when the amount required to pay fixed charges on the substation investment and its operating expenses is about equal to that required to meet the fixed charges and maintenance expense on the feeder equipments which would be required if a substation were not installed. In a growing system it may be advisable to anticipate this point somewhat and install the substation earlier, in order to avoid the loss due to the installation and removal of feeders which are transferred to the substation after but a few years' service.

The point at which the balance between substation cost and feeder cost is struck varies widely with different systems

and classes of construction. In a low-tension direct-current underground system the number of substations must be greater than in an alternating system with 2200-volt mains, because of the shorter radius of action in low-tension systems.

There are also many local conditions to be considered, and two problems are rarely, if ever, identical. With a given class of construction, the radius of distribution and therefore the number of substations is fixed first by the voltage of distribution and second by the load density.

With a feeder loss of 10 per cent at maximum load and a current density of 1 ampere per 1000 c.m., the length of a feeder is approximately one mile per 1000 volts of working pressure. On this basis the radius of distribution at 220 volts is .22 mile or 1100 feet, and at 2200 volts it is 2.2 miles. There are usually some feeders which are longer than this on which the loss runs higher. When these become sufficiently numerous an additional substation becomes desirable.

It is sometimes necessary to establish a substation on account of a large block of load such as an amusement park, large retail store, manufacturing plant or other similar enterprise.

Classes of Substations. — Substations may be divided into two general classes according to the kind of electricity they are designed to distribute — viz., alternating current and direct current. Alternating-current substations are of two general types, transformer and frequency changer.

Direct-current substations are of three types, synchronous-converter, motor-generator and storage-battery.

Substations may also be classed as attended and unattended.

General Principles. — The design of a substation building and equipment must be made with a view to economy of operation, facility of repair and construction work, security

of the service and of employees, and a minimum first cost consistent with these conditions, and with the importance of the service. Where growth is probable, due regard must be had for future extensions.

The appearance of the building should be governed largely by the character of the neighborhood in which it is placed.

A building placed in a factory district naturally follows the type of exterior used for the better class of factory structures, while one placed in a residential district should harmonize with apartment buildings or residences. In central business districts land values are so great that floor area must be conserved and this often necessitates the arrangement of equipment on more than one floor. In such cases the building may also contain some floors which are rented for other uses.

The use of out-of-door transformer installations sometimes makes possible a reduction in the size of the building required, and such construction is often used for the supply of outlying suburbs or towns. In large cities, there are likely to be building ordinances which restrict the use of such types of construction.

In buildings having steel columns, the main converting units and switching equipment must often be laid out with reference to the space available in each " bay " of the building, and the design consists of making the best arrangement of bays for present and future requirements.

In situations where growth is probable, the arrangement of the building must be such that units may be added as required, and with as little interference with the operation of existing equipment as possible.

In certain towns the substation may be combined with an office building serving as district headquarters.

The arrangement of apparatus with regard to the work of construction and repair men should be such as to minimize first cost and operation. Proper provision for repairs will

shorten the time of a shutdown very materially, thus saving loss of income and injured reputation for reliability. No design is permissible which involves unusual risk of interruption to the service. The first cost must be kept within proper limits, since fixed charges on the investment form a considerable part of the cost of electricity supply.

Transformer Substations. — Transformer substations are used where the frequency of the distributing system is the same as that of the transmission lines, and only voltage transformation is necessary. Such a substation consists essentially of incoming transmission lines, oil switches, transformers, distributing switchboard, feeder regulators, switches, instruments, etc., and outgoing feeders.

An arrangement of the equipment is desirable, in which there is sufficient floor space to permit the switches, transformers, and regulators to be placed in regular order on the same floor.

The minimum width of the building required for this is about 40 feet. With a narrower building it is usually necessary to place the regulators or the secondary bus and switches in a basement or on an upper floor.

Extensions are most readily made by placing additional feeder and transformer units side by side along the length of the building, these being added from year to year as the growth of the load may require.

The interior of a transformer substation having oil cooled transformers is illustrated in Fig. 28.

The arrangement of apparatus will, in general, be most desirable when it is such that the flow of energy progresses from entrance to exit in the most direct path possible. This makes the length of cables a minimum, tends to avoid cross-overs, facilitates repairs and results in economical operation.

This is carried out in the arrangement illustrated in Fig. 29. It will be noted that the transmission lines enter at one side of the building, pass through their oil switches to a bus bar, thence through a smaller oil switch to the transformers.

Fig. 28. Oil Cooled Transformers and Regulators.

From the transformers the 2300–4000 volt energy passes through switches to the bus from which it is distributed. The outgoing feeders pass through switches and potential regulators and leave the building at the other side.

Two incoming lines are essential to continuous service. This necessitates a tie switch between them so that the whole load can be carried on either line.

Switches must be provided on each side of the transformers

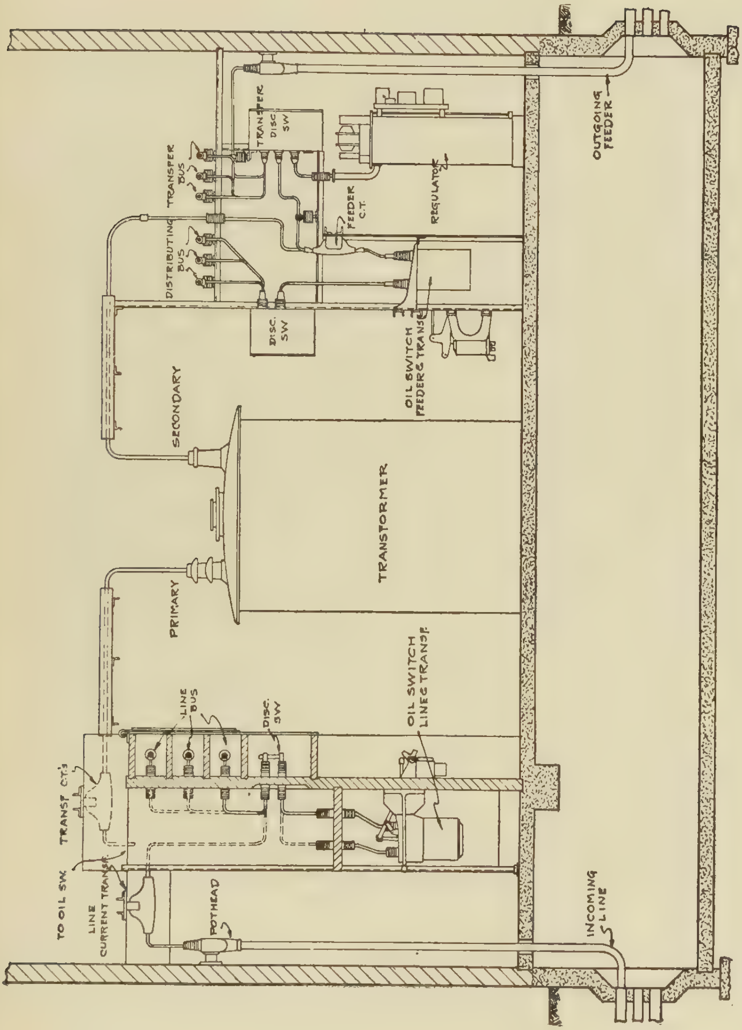


Fig. 29. Transformer Substation.

so that they can be isolated when necessary for repair and maintenance work.

The 2300–4000 volt bus is made double to permit repairs or alterations to be made without interrupting the service. It is also useful at times in permitting longer feeders to be carried at a higher bus pressure or from a different source of power.

The use of an auxiliary bus requires double-throw switches throughout and adds to the first cost of the station. This may be omitted in small substations where there is a single incoming line and only two or three outgoing feeders.

The outgoing feeders leave the bus through single-pole switches and pass through the regulators for the control of the pressure. With a three-wire three-phase system it is usual to employ three-pole switches, but in a four-wire, three-phase system each phase is independent and it is not desirable to open the entire feeder when trouble occurs on one phase only, as is often the case.

In the arrangement suggested in Fig. 29, the high-tension switches occupy space next to the wall, with space between them and the transformers of such width as to permit ready access for inspection, repairs or the replacement of a transformer. The 2300–4000 volt busses are at the rear of the control board, with an aisle between them and the regulators so that they may be accessible. The regulators are motor-operated and are placed near the wall in the path of the outgoing feeders. The control switches for the regulator motors are on the switchboard panels close to the voltmeter, so that the operator may control the pressure while watching the voltmeter. Less expensive hand-controlled regulators are sometimes installed where the arrangement is such that the handles can be extended to the front of the switchboard.

The high-voltage conductors between oil switches and busses are commonly insulated with varnished cambric and supported

on suitable insulators. The lead sheaths of incoming lines and outgoing feeders are terminated in suitable pot heads, which serve to dissipate any static charge which may tend to accumulate and to exclude moisture from the insulation of the cable.

The arrangement suggested in this assumed case is of course an ideal one, since no limitation of space or other local conditions are imposed. In many cases the required floor space is not available or is too valuable for other purposes to justify its use for substation purposes. Under such circumstances, floor space may be economized by placing the potential regulators on a gallery above the switchboard, or the 2300 volt bus and switches in the basement. The latter arrangement brings them in line with the outgoing feeders, and is preferable if the basement is of suitable depth and size to give room to handle and install the apparatus. With a room which is not long enough to permit the transformers to be set in a row it may be necessary to try various groupings of the oil switches and transformers until the best arrangement is found. Each proposed arrangement must be considered with reference to the disposition of the apparatus and connections in the basement as well as on the main floor.

Switching Apparatus. — The switches on the incoming line must be capable of opening the entire load under emergency conditions, and should therefore be of the oil break type with fireproof compartments for each pole. These switches must be equipped for protection from short circuit, which necessitates a set of current transformers on each line. Suitable space must be provided for these near the switch, as well as for the relays.

The switches are operated by alternating current with auxiliary hand control in the absence of any source of direct current for this purpose. The switches controlling the trans-

formers may be of the tank type of oil switch, the transformers being arranged so that they can be disconnected entirely on both sides. The switches on the line side should be protected by overload relays, while those on the 2300 volt bus should be protected by reverse-energy relays to guard against the failure of a transformer coil.

These switches may be of the type which is closed against a spring by hand and opens automatically when tripped by the relay. The relays for primary and secondary of the transformers may conveniently be located on the switchboard panel which carries the secondary switch. The current transformers should be located in a place where they are convenient to the leads of the main transformers.

The switches on the outgoing four-wire feeders should be of the hand-closing, spring-actuated type of circuit breaker.

Outgoing feeder switches should have a capacity of 150 to 300 amperes at 2300 volts. It is not desirable to load distributing feeders more heavily than this, as it is as much as can be properly distributed from the feeder end with good distribution of pressure on the primary mains.

Transformers. — The transformer equipment may be of the air-blast, oil-cooled or water-cooled type. Oil-insulated transformers are less subject to puncture by lightning or high-potential surges and are usually used with overhead lines for this reason. Air-blast transformers are the least expensive in first cost, but involve apparatus and ducts for the fresh-air supply. In a large substation this may become a serious difficulty owing to the space required for the air ducts. The circulation of water or oil permits more rapid cooling and is therefore desirable in the larger units in order to keep the size and first cost of the transformer within reasonable limits.

Where floor space is limited, air-cooled units are desirable, as they are smaller in external dimensions and are designed

with a view to occupying a rectangular floor space of very small area.

With oil-cooled units of larger sizes it is advisable to provide drains to a sewer for the transformer oil so that in case it should become ignited it could be drained off to assist in extinguishing the fire.

With large high voltage transmission systems it is usual to install the transformers in separate compartments to guard against the spread of an arc or flames from burning oil to adjacent transformers. With units of 2000 kw. and larger this expense is usually justified in view of the importance of the service and the investment involved.

Reserve Capacity. — The selection of the size and number of units for a substation is a matter of great importance from both operating and investment standpoints.

The units should be as large as possible to insure low first cost per kilowatt and high efficiency, and numerous enough to leave sufficient working capacity in case a unit fails.

In a three-phase station, the use of two units on each phase would result in a reduction of 50 per cent in capacity on one phase if a unit fails. If the units are selected with a reserve capacity of 30 per cent, the load can be carried by running one unit at about 50 per cent overload until a spare unit is put in place of the defective one. Where the service is important a spare unit should be available at all times for emergencies. In a system with several substations, two or three sizes may be standardized, one of each being carried as reserve. Where there are several substations it is sometimes possible to secure reserve in part through tie lines from adjacent stations which may have spare capacity.

Switchboard. — The switchboard panels carrying control switches should be located in a position where the instruments

may be readily observed by the operator, and at a sufficient distance from the wall to give reasonably good access for construction and repair work. It carries no high-tension connections except where the feeder switches are of the hand-operated type, in which case they are preferably mounted on the panel with the instruments. Where remote control switches are employed, the switchboard carries only secondary low-pressure wiring, such as instrument connections, remote control circuits, compensator circuits and the like. Such a board must be located in a part of the room where it is accessible to the operator. The operation of remote control switches should be indicated to the operator by pilot lamps of red and green on the operating board.

Each feeder should be provided with an ammeter as a means of indication of the load carried and a voltmeter in connection with a line drop compensator to indicate the feeder end pressure to the operator. A power factor indicator is a desirable accessory on the main bus.

The transformer panels should be provided with ammeters and a bus voltmeter for each bus and phase. The control wiring for the transformer switches is also brought to the transformer panels.

The design of the switchboard should be carried out with a view to making as economical an arrangement of the apparatus as is consistent with safety of installation and operation.

The arrangement of the wiring for instruments, relays and similar apparatus should be carefully made with a view to making it secure from failure, accessible for testing and repair work, and neat in appearance. Where a number of wires are grouped on one or two panels, the use of terminal boards for testing and repair purposes is very desirable. These should be placed so that an instrument adjuster can get at them conveniently without disturbing the connections at the instrument terminals.

The switchboard should be of fireproof materials, marble or slate on angle iron frames being the most commonly used construction. The arrangement of switches and bus connections should be such as to minimize the danger of the spread of an arc. The location and arrangement should permit of necessary extensions which may be required in connection with the addition of feeders from year to year.

Frequency Changer Substations. — The essential difference between the frequency changing substation and a transformer substation lies in the presence of motor generators. The incoming lines with their high-tension switching equipment and outgoing feeders with their switchboard and regulators are practically identical under equivalent conditions of load and space available in the two kinds of substations.

The motor generator outfit requires about the same floor space as an equal capacity in single-phase transformers when the motor is wound for the transmission voltage and the two machines are mounted on a common bedplate with a short shaft and two bearings. When designed in the vertical form there is some saving in floor space in the larger units.

Where the transmission is at a pressure too high for the motor windings direct, the motor generators require transformers and this increases the required floor space of the substation very materially.

This substation includes exciters for the fields of the motor generators and a high-tension starting bus fed by a reactance coil, for use in bringing the synchronous motors up to speed, at reduced pressure. A single reactance coil is provided together with double-throw switches on the motors so that any motor can be thrown to the starting bus and started from the one starting coil, the cost of the bus and double-throw switches being less than that of extra reactance coils. Dupli-

cate exciters driven by separate motors at the transmission frequency should be provided, as they must be started at times when the station is shut down, and reserve capacity must be available in case repairs become necessary on either

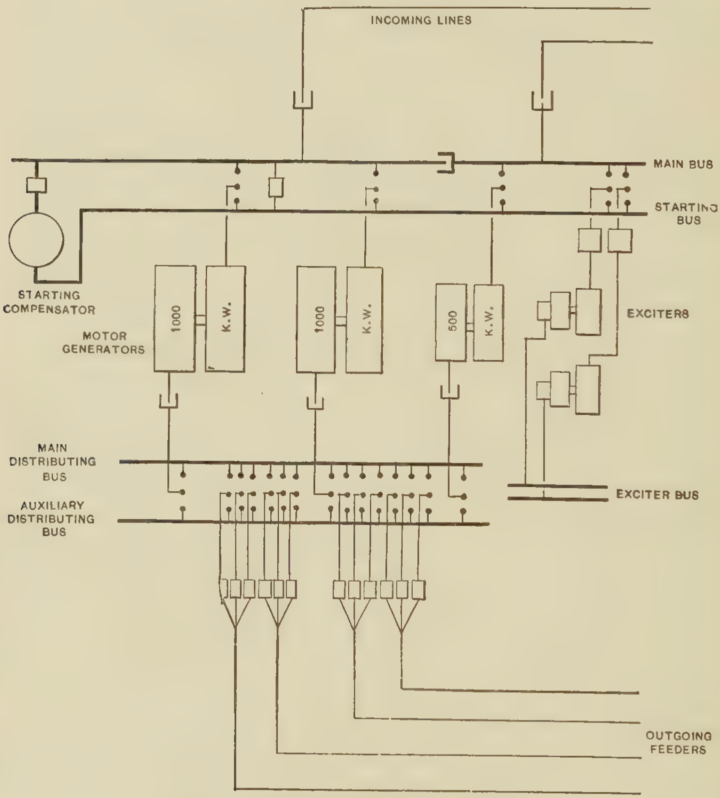


Fig. 30. Frequency Changer Substation.

unit. In some cases it is sufficient to have two exciter units separately driven, the others being driven by connection to the main units.

Where Tirrill regulators are used, it is dsirable to have them control the pressure on the 60-cycle generators only.

This necessitates the use of a separate direct current bus for the synchronous motor excitation.

The exciter units being less than 100 kw., it is usually not practicable to use motors wound for the line voltage to drive them. This requires a set of transformers and permits the use of low-voltage induction motors which are less sensitive to shocks on the transmission system. The entire control of the exciter may thus be placed on a low-voltage switchboard.

One of the chief points of interest about such a substation is the method of starting and synchronizing the motor generator sets. When a unit is to be put in service it is connected to a starting bus supplied by an autotransformer at 40 per cent of the transmission line pressure. The switches controlling the direct current for the fields of the motor are left open. The oil switch controlling the motor is then closed to the starting bus and the unit begins to revolve as a hysteresis and induction motor. When the unit is at approximately synchronous speed the field is excited, thus drawing the unit into step as a synchronous motor. This usually causes a rush of current for a very brief interval of time, as the machine is likely to be out of phase at the instant the fields are excited.

When the conversion is from 25 to 60 cycles this usually does not complete the operation of synchronizing, as the 60-cycle generator is not necessarily in phase with its bus when the 25-cycle motor has been synchronized. The ratio of the number of field poles on the 25-cycle motor to those on the 60-cycle generator must be as 25 is to 60 or as 10 is to 24. When a 10-pole field is mounted on the same shaft with a 24-pole field, as is usually the case in a 25–60-cycle frequency changer, only one set of poles on each field can be lined up in the same radial plane. In Fig. 31, the poles which are aligned in the same radial plane are represented by the heavy diameters. When the 25-cycle machines are synchronized, any

of the five sets of poles on the incoming machine may fall into step with the poles represented by the heavy line on the operating unit. When the 25-cycle machine has fallen into step, as in Fig. 32, on the pair of poles next to the one repre-

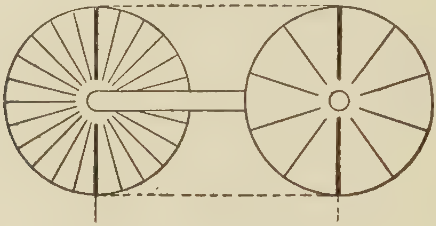


Fig. 31. Poles of Frequency Changer.

sented by the heavy line in Fig. 31, the incoming 60-cycle machine is held out of phase with the operating unit as shown by the dotted vertical line. If the rotation is counterclockwise, the machines can be brought into phase by cutting off

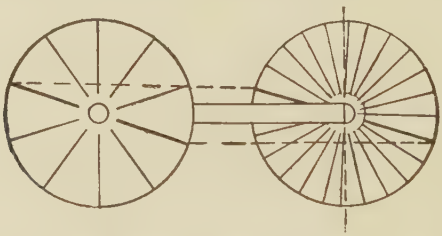


Fig. 32. Displacement of Phase, Frequency Changer.

the supply of energy from the incoming machine and allowing it to slip back, one pair of poles at a time, until the heavy lines are in phase with each other. The machines are then in phase on both 25- and 60-cycle ends. A special synchroscope is employed which has five points corresponding to the five positions in which it is possible to bring the 60-cycle machines into synchronism. The dial is shown in Fig. 33.

In synchronizing if the 60-cycle pointer takes position No. 4, it is necessary to "slip poles" four times before the 60-cycle machines can be thrown in parallel.

Fig. 33.

These complications do not arise in synchronizing a single frequency changer with a 60-cycle generator driven by a prime mover, as the prime mover can be adjusted to bring it into phase.

Direct-current Substations. — The direct-current substation receives high-tension alternating current energy and converts it to low-tension continuous current energy, for distribution. The battery substation receives continuous low-tension energy and delivers the same, the function of the battery being to store energy for use in an emergency.

Synchronous converters are usually employed as the medium through which alternating current energy is transformed to direct current energy, this type of equipment being more efficient than motor generators and lower in cost.

The efficiency of the converter runs from 90 to 93 per cent at loads of 50 to 100 per cent of rating, whereas the efficiency of motor generator sets under the same conditions is from 83 to 88 per cent.

The mercury arc rectifier has been developed as a source of direct current energy in Europe; chiefly, however, for the higher voltages used in railway service. This equipment has an efficiency of 95 to 97 per cent and has the further advantage of requiring little attention. At voltages below 300, the first cost and space required for capacities of 3000 kw. or more are more than for synchronous converters.

Motor-Generator Substations. — Motor generator converting sets for substations are preferably wound for the transmission voltage where pressures less than 15,000 volts are

used, as the extra cost and space required for the transformers is a considerable item. Direct current is delivered to the distributing bus by the generator.

Synchronous motor sets are started preferably from the direct-current side in order to avoid disturbance in the transmission system, due to large starting currents. They are then synchronized and connected in parallel with the transmission system. Induction motor sets are started by the use of resistance in the rotor circuits which gives good starting torque with a starting current little in excess of full-load current. The induction sets are started first in an emergency, thus furnishing direct current from which to start the synchronous sets. The high-tension line equipment is similar to that outlined for a transformer substation. Control of the direct-current pressure is had by means of the field rheostats of the generators.

Synchronous Converter Substations. — In converter substations the electricity received from the transmission system passes through suitable oil-switching arrangements to step-down transformers which deliver a secondary pressure suitable for the rotary converter. From the transformers the current passes through a potential regulator to the collector rings of the converter and thence through its windings to the commutator from which direct current is delivered to the brushes. The direct current passes through a circuit breaker and switch to its bus bar, from which the feeders are carried to the distributing mains. Two or more direct-current bus bars are usually provided to facilitate the regulation of pressure during the period of heavy load.

The three-phase shell type of transformer, air cooled, has been used quite generally for this class of service owing to the economy in first cost and in floor space. The air for cooling is blown through ducts within the case, and in substations

of 2000 kw. or more it is sometimes necessary to provide ducts to carry the heated air outside the building. This requires a suitable blowing outfit and space for air chambers under the transformers.

Types of Converters. — Synchronous converters are provided with shunt or compound field circuits. They may also have interpole windings and a synchronous booster for pressure control.

Shunt machines were formerly used for lighting work exclusively. With the shunt machine it is necessary to use a regulator for control of the direct-current pressure, since the variation of the shunt field strength changes both power factor and pressure, and the use of the shunt field to control pressure produces undesirable power factor under certain conditions of load and pressure on the incoming line.

The adaptation of the interpole field to synchronous converters greatly improved conditions of commutation and permitted the development of larger sizes of all converters than had previously been permissible. The maximum size available prior to 1910 was 2000 kw., while converters of twice this size were put into service within a few years after the introduction of the first machines of the interpole type.

A modification of the interpole machine known as the split-pole converter was developed, but has not been generally employed. The split-pole machine has three sets of field windings with separate rheostat control, the purpose of which is to secure variation in pressure by changing the form of the voltage wave without affecting the power factor seriously. The manipulation of the fields is rather complicated and the machine is somewhat larger than other types of converters.

The space required for the induction regulator and its connections, and its liability to injury when subjected to the mechanical shock of a short circuit, suggested the desirability

of the use of the synchronous booster type of converter with interpoles to assist in commutation.

This machine carries an alternator on the main shaft with its windings in series with those of the converter armature, as shown in Fig. 34.

The booster is wound to give a range of about 10 per cent of the rated pressure of the machine. Its field is reversible and this gives a range of 20 per cent in the pressure delivered

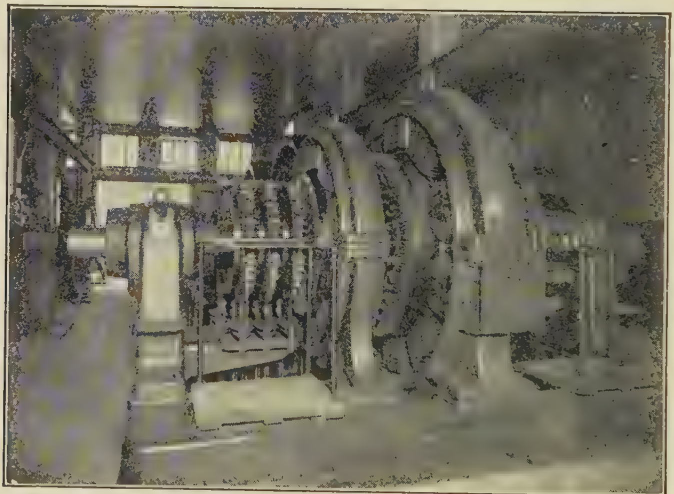


Fig. 34. Booster Type Converter.

to the direct-current bus bar. This range can be more readily increased to meet an emergency than is possible where an induction regulator is employed.

The advantages of simplicity of connections and greater flexibility are such that this type of converter has been generally adopted in recent years.

In substations having units of 500 kw. or larger it is desirable to use converters wound for the voltage across the outer wires, in order to avoid the multiplication of the number of units, and the increased expense incident thereto. The unbalance

of the system may be cared for by one pair of 110-volt machines or by a motor-generator balancer set or by the use of six-phase diametrically connected transformer secondaries arranged as in Fig. 35. The latter plan has the advantage that no 110-volt machines are required in the substation. The neutral of the direct-current system is connected directly to the secondary neutral of the transformers and any unbalance is thus cared for. The unbalance in a large system is rarely over 5 per cent and the scheme is found very satisfactory in most instances.

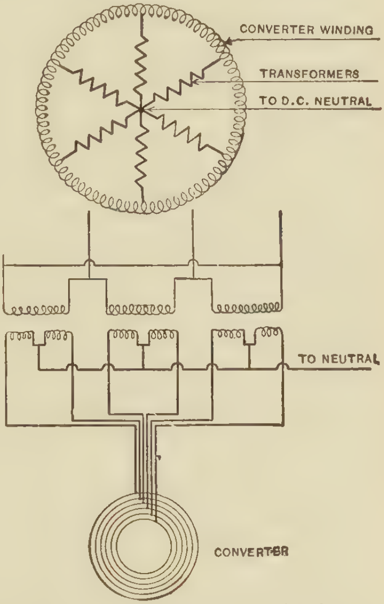


Fig. 35. Connections of Six-phase Converter.

The use of the six-phase connection and converter winding reduces the length of the path traveled by the current in passing through the armature and thus reduces the losses and the heating. Theoretical calculations based on sine waves indicate that a direct-current generator rated at 100 kw. may be rated at 131 kw. as a three-phase converter, or at 194 kw. as a six-phase converter, or the same rise of temperature.

The theoretical ratio of transformation in voltage in passing from the collector rings on the alternating-current side to the direct-current brushes is as 61 to 100 in a three-phase converter and as 71 to 100 in a six-phase converter. These ratios are based on the assumption of a sine wave of E.M.F. and may vary somewhat in actual practice.

It is usual to protect the converter by a reverse-current relay which opens the circuit breaker in case the flow of energy is reversed, and shuts the machine down. Without such protection the reverse current may weaken the field of the converter and cause it to accelerate quickly to a dangerous speed. The reverse-current relay does not operate below 10 per cent of full load, and a speed limit consisting of a centrifugal switch is often provided as further insurance against dangerous peripheral speeds. The speed limit is rarely called upon to act and should, therefore, be tested at regular intervals. Accidents to converters in which machines have been wrecked have occurred in nearly all large systems, and the provision of such accessories must not be overlooked where the unit operates in parallel with a direct-current system having other sources of supply.

Starting of Converters. — The arrangement of starting devices for synchronous converters is a matter of great importance, as it must be possible to start them quickly and without serious disturbance to the system in regular operation and in emergency. The converter may be started by a supply of current from either side or by a starting motor direct connected to the shaft. When started from the direct-current side a rheostat is used in series with the armature, as in starting a direct-current motor. The starting current, however, has two paths, one through the converter windings from brush to brush, and another through the collector rings to the transformer coils and thence back again to the converter armature. While the converter is turning slowly, the frequency of reversal of the current through the transformer coils is low and the choking effect is small. The starting current from the direct-current side is, therefore, more than that of a motor of the same size without load. When the machine has come up to speed the potential regulator is ad-

justed to bring the pressure of the converter up to that of the transmission system, and the rotary is synchronized with the transmission system and connected to it. The field and regulator are manipulated to bring the power factor up to unity and to adjust the load carried by the unit to the desired amount.

In case a total shutdown of the system removes the supply of direct current for starting, means must be at hand for starting from the alternating current supply. Converters may be started from the alternating side with the field coils open as in starting a synchronous motor, and the pressure reduced to about half normal pressure to keep the starting current within limits. This may be done by means of a starting compensator on the high-tension side of the transformer or by means of taps on the secondary winding. The latter is preferable as no autotransformer or extra high-tension switching operations are required.

In this method after the machine is brought up to speed its fields are excited and the polarity noted, as it may come up reversed. If so, the direct-current voltmeter on the machine gives a negative reading. The field connections are then reversed by means of a switch provided for the purpose and the machine slips back one pole. As soon as it has done so the direct-current voltmeter swings to a positive reading, when the field is again reversed and the polarity remains correct. The starting switch is then thrown to the full pressure, the machine pressure is equalized and it is connected to the direct-current bus.

The current required in starting from the alternating-current side is from 150 per cent to 200 per cent of full-load current on a 500 kw. converter and somewhat less on larger sizes. The direct-current starting current, however, is but 25 to 30 per cent of full-load current. This small starting current makes this method preferable in cases where there

are several machines or where the direct-current distributing system has sufficient capacity to furnish the starting current without serious disturbance. In such cases the normal method of starting is from the direct-current end.

Sufficient machines should be equipped for alternating-current starting in a given substation to insure a supply of direct current for starting the other units. Where sufficient storage battery capacity is installed the direct-current supply may be relied upon at all times.

Low-tension Switchboards. — The direct-current distributing equipment being operated at low potential is radically different from the 2200-volt alternating-current equipment before described. The bus bars are of bare copper about half an inch thick and from three to six inches wide, built up, with air spaces between for radiation, to the required number to carry the current. These are mounted at the back of the switchboard so that the connections to the generator and feeder switches may be as short as possible. The chief consideration in the design of such boards is an arrangement using a minimum length of copper, as it is necessarily of heavy cross-section. The board should, therefore, be as short as possible, but the opposite polarities should not be so close as to endanger the service in case a short circuit is made.

The arrangement shown in Fig. 36 and Fig. 37 accomplishes these objects very effectively. The upper row of switches are all of one polarity and the lower of another. The neutral conductor need not be switched and is connected direct to the neutral bus. The separation is ample and the length of bus-bar copper per feeder is about 6 inches for each pole of the bus.

This close spacing necessitates the use of the edgewise type of ammeter, an instrument being placed on each side of the three-wire feeder. The location of the polarities is usu-

ally standardized for the sake of uniformity. That is, the positive bus is placed above or at the right, and the negative below or at the left, or *vice versa*. Separate voltmeters are not

Fig. 36. Rear of Low Tension Switchboard.

necessary for each feeder in direct-current networks, but the pressure wires brought from the feeder ends are terminated in a multiple-point switch so arranged that the pressures on the feeders may be read on a single voltmeter successively.

The bus pressure is usually indicated by a separate voltmeter, as this pressure should be visible to the operator at all times.

Regulation. — The individual regulation of feeder pressure is not necessary in direct-current systems except for very long

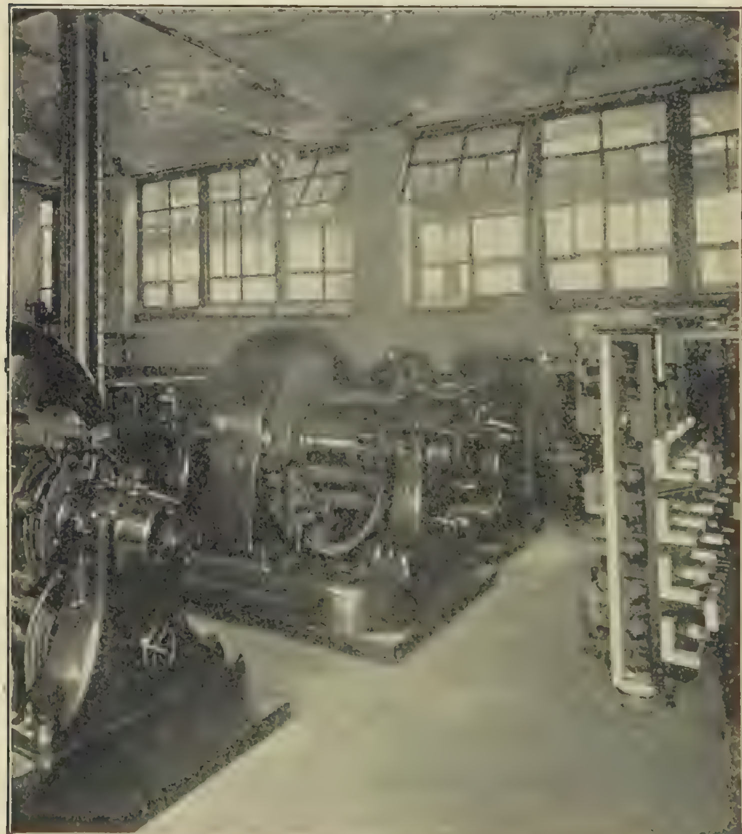


Fig. 37. Synchronous Converter Substation.

feeders which may be equipped with a booster set, or with very short feeders which may have a resistance in series to absorb part of the pressure.

Booster sets for use on three-wire feeders commonly consist of two generators of sufficient ampere capacity to carry the full load of the feeder and voltage range sufficient to make up for the feeder loss, usually at least 40 to 50 volts. These are driven by direct connection to a 230-volt motor of proper capacity. The booster generator fields must be designed to operate throughout the full range of pressure without trouble at the brushes, and must have independent field-rheostat control in order to permit compensation for drop on the neutral in case of unbalanced load. The location of a booster set should be such that the length of the feeder cables which are looped through the booster will be as short as circumstances will permit.

Feeder resistances are to be avoided as far as possible, and are usually not necessary on more than one or two very short feeders. Where necessary, they must be of a design which will carry the feeder current at full load without excessive temperature rise. This necessitates a special design of rheostat. Wire coils have been used for smaller feeders, but for those carrying 500 amperes and upward, strips of heavy, galvanized sheet-iron, mounted on suitable insulating supports and surrounded with a wire netting for protection, have given good results. There should be several sections so that the operator can adjust the resistance for different loads.

Storage Battery Stations. — One of the principal advantages of the direct-current system of distribution is the possibility of the use of a storage battery reserve. Before the use of the battery became general, it was not an uncommon thing in the larger systems to have the service seriously interrupted through accident in the generating or transmission system. With the introduction of the storage battery these interruptions were largely obviated, only serious accidents affecting the major part of the system being the cause of

shutdowns. The smaller disturbances in a large system protected by batteries do not appreciably affect the service. The usual arrangement of battery connections is shown in Fig. 38. Taps are brought out from the end cells to a number of

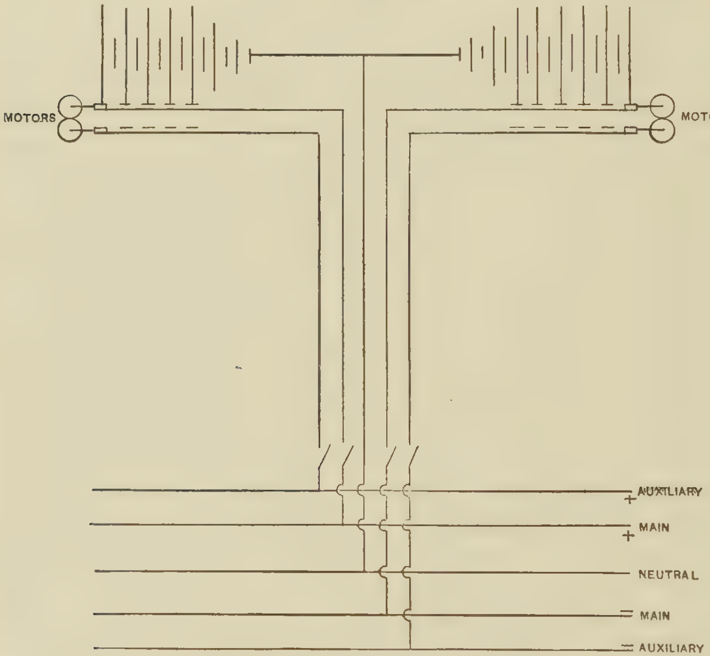


Fig. 38. Battery End Cell Connections.

terminals arranged to permit the battery to be discharged at the desired voltage.

Connection is made from each end-cell terminal to a bus bar by a sliding contact. The voltage of each cell being about two volts, the pressure delivered by the battery to the bus bar varies according to the position of the sliding contact. When the battery is required to discharge, the sliding contacts are moved toward the outer ends, thus raising the pressure of the battery and causing it to deliver energy to the bus bar.

When no energy is required from the battery the end-cell contact is set so that the battery pressure and the bus pressure balance and the battery floats on the system. In case of a reduction in the bus pressure due to a failure in the supply of energy, the battery immediately begins to discharge to the bus, thus tending to hold the pressure up and preventing a complete interruption of service. The extent of the interference depends upon the relative capacity of the battery and the load on the bus at the time. During the hours of smaller load the operator's adjustment of the end-cell switches is sufficient to restore the pressure to normal in a very short time, so that the consumer notices nothing beyond a slight flickering in the lights.

The maximum load in a large system is usually considerably greater than the average load, and it is not feasible to provide sufficient battery to care for a serious accident at the hour of the maximum. The maintenance of batteries being expensive, it is usual to provide about 10 to 20 per cent of the maximum load in battery capacity.

Two or three busses are provided, so that the battery may discharge simultaneously to main and auxiliary busses at different pressures if required. It is desirable to keep the battery floating on the main bus while it is being charged through another bus. The battery may be charged through a booster from the main bus, or from a separate converter or generator wound for the higher pressure required for full charging.

The battery is usually arranged for motor control of the end-cell switches with indicators on the switchboard to show the operator the position of the end-cell switches on each bus, ammeters on each bus and pressure connections by which the voltage of individual cells may be taken.

The most essential points in the construction of a battery station are ample space, proper ventilation and sufficient strength to support the weight of the cells.

The cells are set side by side so that the plates of neighboring cells can be joined together by a lead bar without the use of copper bus-bar work as far as possible. The floor space required by a battery is much more than that which is needed for an equal capacity in converting apparatus. It is sometimes necessary on this account to put parts of a battery on separate floors.

The use of sulphuric acid as an electrolyte, and the ebullition of gases from the battery, tend to keep the air in a battery room heavily laden with sulphuric acid vapor. This acid corrodes all the common metals except lead, as well as many organic substances. It is therefore necessary to protect all structural steel work with building tile and plaster and to keep all copper bus work well painted. As a further means of reducing the corrosive action ample ventilation must be provided. Where natural ventilation cannot be secured, fans must be provided discharging through a stack. During the summer months open windows may be relied upon where batteries are sufficiently remote from adjoining buildings to avoid interference with the rights of others. The floor of the battery room must be arranged to drain off any leakage of the electrolyte. The use of cement floors is not permissible on account of the action of the acid. It is therefore usual to lay a floor consisting of a layer of roofing paper well coated with compound and over this a floor of vitrified tile brick with the spaces between the bricks carefully filled with compound. Such a floor will not permit the leakage of any electrolyte to the lower floors, and is not affected materially by the acid.

The operation of the battery being affected by the specific gravity of the electrolyte, it is necessary to have a supply of pure water for the purpose of diluting the acid at intervals. The provision of facilities for the storage or manufacture of distilled water is therefore usually necessary.

The end-cell connections are preferably terminated on an end-cell switch built into one wall of the battery room and facing toward the outside. This keeps the strong acid fumes away from the end-cell switch and other substation apparatus.

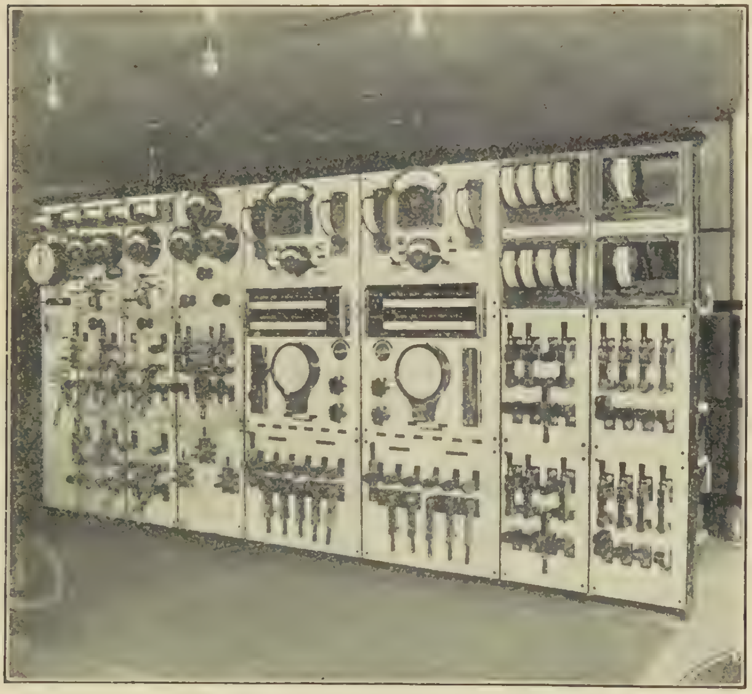


Fig. 39. Storage Battery Switchboard.

A battery switchboard with end-cell indicators and controlling devices is illustrated in Fig. 39.

Unattended Substations. — Attendance being a large part of the cost of operating a substation, much attention has been devoted to control equipment by which many of the more frequent operations are performed by a system of relays which are arranged to function in a predetermined order and

thereby to switch converting equipment into and out of service as the conditions of load on the system require.

The equipment is so designed that a unit is cut out when the load falls below an amount which makes it unnecessary that it continue to operate. If there are several units, they are adjusted to cut out at different points. For instance, with 3 units, the first may be set to cut off at 60 to 65 per cent of full load, the second at 45 to 50 per cent, and the third would run continuously. In the case of a network of low-tension mains, the third unit might also be arranged to cut off at 30 to 35 per cent load, thus transferring the load to a neighboring, but attended, substation. With increasing load, the first unit may be set to cut itself in at the point when the pressure on the network falls below a certain point. Other units would cut in when the load on the operating units reaches full load or a small overload.

In direct current stations the starting relays control the supply of energy to a starting compensator, which brings the unit up to speed from the alternating current supply, and, when the direct pressure is normal, closes the direct current connection to the bus. The stopping relays open the connection to the bus and then cut off the alternating current supply. In both operations the relays are so interlocked as to insure proper sequence of the operation of switches.

Circuit breakers on supply lines are arranged to reclose once or twice automatically, thus restoring the supply promptly from lines which had been opened by trouble at some other point in the system.

In alternating current substations, supplying distribution feeders, the automatic reclosing relay is sometimes provided on the outgoing feeders.

This promptly restores the service in cases where the trouble on the circuit was of a temporary nature.

Equipment such as automatic control on potential regula-

tors, motors, operating auxiliary apparatus, and similar accessories are kept in order by a daily inspection and adjustment when needed.

The first cost of an automatically controlled substation is necessarily much more than that of an attended substation, though not so much as to make the automatic substation uneconomical. The high first cost led to the development of methods of supervising unattended substations by a system of remote control.

Where there are attended substations in operation within a radius of 2 or 3 miles, control may be had by a pilot cable of 7 conductors by which the operator at an attended substation may control switching operations at the unattended substation.

Industrial Substations. — Where energy is supplied to industries in amounts of 500 kw. or more, it is often more economical to render the service from a high voltage line, thus relieving the substation and distributing system of a block of load which would otherwise absorb expensive capacity unnecessarily.

Service to such users is given by a transformer installation placed out-of-doors if supplied by overhead lines, or indoors if by cables.

Indoor installations include oil circuit breakers, current and potential transformers, and relays, and these, with the main power and lighting transformers, constitute an industrial transformer room or substation. Smaller installations, and those whose continuity of supply is less exacting, are sometimes served by a single tap line connection. Others are served by a loop or by taps from two lines. The equipment varies with the size of the installation and the service requirements.

A few of the more commonly used schemes of connection are shown in Fig. 40.

Where a single line, without a reserve cable on the premises, is sufficient to meet service requirements, the layout is simple and a group of equipment such as that shown in (*a*) is used. It includes an oil-switch, isolating-switch, and overload relay. The oil-switch is usually of the manually closed type of circuit breaker.

Where service from a tap does not satisfy the requirements of continuity and promptness of restoration, a second cable

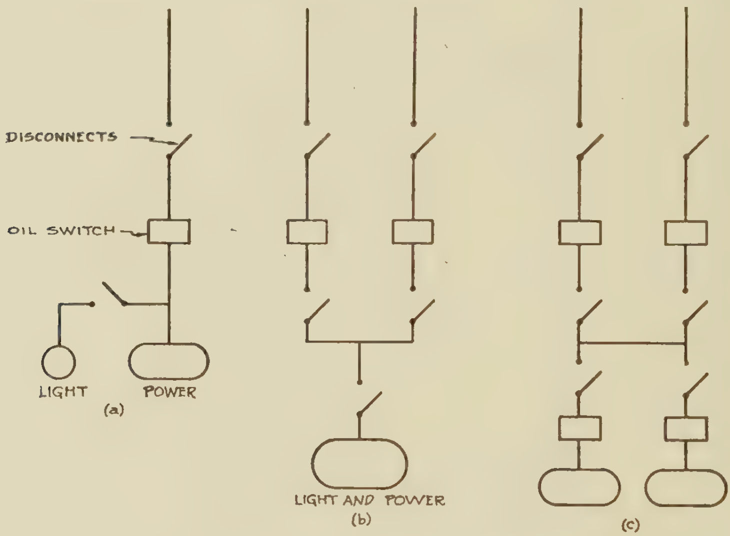


Fig. 40. Connections, Industrial Sub-stations.

must be introduced. Such a connection is shown in (*b*). This necessitates the addition of a circuit breaker for the transformer. This breaker is set to open at a lower current value than the line breakers, thus avoiding the operation of line breakers when not necessary.

Isolating-switches are needed to permit repair and maintenance work on the breakers without interrupting service or endangering workmen.

When the user's demand is so large as to make the use of two transformers desirable, the arrangement takes the form shown in (*c*). The additional circuit breaker for the second transformer necessitates more facilities for isolation and additional necessary equipment for relay control.

In the larger cities, the amount of power back of the supply circuit is so great that the circuit breakers on the incoming line must be of greater rupturing capacity than those controlling the transformers, and are, therefore, usually of the compartment type. This separation is necessary to prevent the breaker from throwing oil or flame to adjacent equipment.

The room provided for an industrial substation must be equipped with suitable ventilation to prevent overheating and carry away smoke if it should be necessary. The construction should be fireproof and the space ample to permit removal of equipment for repair when necessary. This requires a room having dimensions of about 16 x 25 feet in the average installation.

CHAPTER IV

VOLTAGE REGULATION

Incandescent Lamps. — The application of electricity to the lighting of buildings made slow progress in the earlier years of the industry until Edison developed the incandescent lamp for use in sizes equivalent to the gas lighting units of approximately 16 candle-power, which were then employed. Edison's carbon filament lamp, with improvements gained by experience in manufacture, was generally used from its introduction in the year 1880 until 1907, when the first Tungsten filament lamps were introduced for commercial use.

The Tungsten lamp produced about twice as much light per watt expended as the best carbon lamp had given, and, within 5 years, had largely displaced the carbon filament lamp.

The fragile pressed filament, used at first, was replaced within a very few years by a drawn wire filament of sufficient strength to eliminate all unusual precautions in shipment.

In 1913, another type of Tungsten lamp was developed, in which the vacuum within the lamp was abandoned and the space was filled with an inert gas, making what is known as the gas-filled lamp. The effect of this was to permit the filament to be operated at a higher temperature with the same rate of evaporation, and, thus, more light was obtained for the same energy consumption and the same useful life.

The gas-filled lamp was found to have its greatest advantage over the vacuum lamp, in the sizes above 50 watts, and the gas-filled lamp therefore finds its greatest usefulness in commercial and outdoor installations, where larger lighting units are applicable.

Relation of Voltage to Lamp Life and Efficiency.—The life and efficiency of a Tungsten incandescent lamp are closely related to the voltage which is maintained at the lamp socket.

The percentage variation of the watts consumed per candle-power (efficiency) and of the candle-power of a Tungsten lamp, as the voltage is varied, are shown in Fig. 41.

It will be seen that an increase of 2 per cent in voltage produces an increase of about 8 per cent in candle-power and 4 per cent in efficiency. Likewise, a decrease of 2 per cent in voltage results in a decrease of about 7 per cent in the candle-power of the lamp.

The life of the lamp is affected by changes in the voltage at the lamp terminals even more rapidly than the candle-power. A lamp burned at 5 per cent above normal voltage will fail at about half the normal life of the lamp, and the life will be doubled if the lamp is burned throughout its life at a pressure about 5 per cent below normal.

The rated voltage of a lamp is, therefore, fixed at a value which will give a lamp life, which will make the cost of lamp renewals consistent with the total cost of light. This varies with the cost of energy, but, for average conditions, it has been the practice of American manufacturers to make lamps having a normal average life of 1000 hours for general service.

The cost of lamp renewals per kilowatt-hour varies with the life and with the cost of the lamp.

Thus, a 50 watt lamp, costing 30 cents, and lasting 1000 hours, will have consumed 50 kilowatt-hours at the end of its life. The cost of lamp renewals in such a case is, therefore, .6 cent per kilowatt-hour. If the lamp were burned at a pressure such as to reduce the life to 500 hours, the cost per kilowatt-hour would be increased to 1.2 cents.

The cost of lamp renewals is included in the service rates to retail users in many American cities, and the effect of shortened lamp life on lamp costs makes it very important that

Fig. 41. Incandescent Lamp Characteristics

voltages be not allowed to run much above normal at the lamp socket.

This, combined with the necessity of preventing low voltage to avoid poor lighting service, has resulted in the provision of means for carefully controlling the pressure impressed on distribution circuits.

The control of the pressure is accomplished by the variation of the generator pressure at the power station bus, by voltage taps on transformers supplying transmission lines and substation busses, and by the use of potential regulators on the individual feeders of an alternating current distribution system.

Low-tension Networks. — In low-tension networks, which are generally operated with direct current, uniform pressure is maintained on the mains by varying the bus pressure as the load changes and by the fact that the regulation of pressure is to some extent automatic. When a heavy load is placed at any point on a network the pressure near that point is lowered somewhat, causing current to flow from all adjacent feeders toward the low point in proportion to the capacity of the mains in the vicinity of the load. The heavy load is thus carried in part by each of the feeders nearest the low point, which tends to support the pressure in that locality. When the adjacent feeders take the added load the pressure at their ends is held by raising the bus pressure, and the system tends thus to automatically equalize the pressure within certain limits.

The different lengths and sizes of the feeders tend, however, to produce higher pressure on the network near the station and lower pressure at remote points during the heavy-load period. In the earlier development of networks it was customary to insert resistances in the feeders to keep the pressure down on the short feeders and to afford means of shifting

load from one feeder to another. This practice was discontinued as a general thing because of the inherent tendency of the network to regulate the pressure automatically. The loss of energy in feeder resistances was a considerable item and the space required is considerable where feeder loads are heavy. They are used in modern practice only for very short feeders, where regulation cannot be secured without them.

It is found desirable to provide two or more separate busses and to arrange the switchboard so that the shorter feeders can be carried on one at a lower pressure and the longer feeders on the other busses at higher pressures. Each bus is supplied from a source which can be independently regulated, and each zone may therefore be carried at a pressure suited to average drop on its feeders.

This arrangement necessarily requires a sufficient number of sources of supply of the proper capacity to carry the loads on the several busses, and is therefore only applicable to stations and substations having several units.

The operation of several busses is necessary only during the hours of heavy load since the difference between the drop on the longer and shorter feeders is not so great during the hours of light load, and all feeders can be carried from one bus.

It is often practicable to prevent pressure from running too high during the light-load period by opening a part of the feeders running to a district, transferring the load to the remaining feeders and increasing the drop on them.

With very long feeders it is sometimes necessary to install a motor-driven booster in series with the feeders to hold the pressure up. Such boosters may be compounded to automatically maintain constant pressure at the feeder end as the load changes. Where storage batteries equipped with end-cell switches are available, it is sometimes feasible to put the longer feeders on the battery through a separate bus and thus avoid the use of a booster. The installation of a

booster is not justified until the fixed charges on the cost of the feeder capacity required to produce equivalent results exceed the fixed charges on cost of the booster equipment plus the value of the loss due to its operation.

It is usual in low-tension networks to run pressure wires from the principal feeder ends back to the station where they are connected to a multiple-point switch in such a way that a voltmeter may be connected to the pressure wires of any feeder, and the pressure at any point in the network may thus readily be known at any time.

In operating the system a feeder which represents the average condition in any zone is selected as a standard feeder. The pressure wires of this feeder are run to a separate voltmeter which is used for regulating the bus which supplies the zone. The operator manipulates the field rheostat of the machines which are carrying the load as may be necessary to hold the pressure as indicated by the voltmeter on the standard feeder constant. A similar standard feeder is required for each bus, and in large systems a second standard is often maintained for use in case of emergency.

In stations where a storage battery auxiliary is provided, it is usual to adjust the battery pressure to that of the bus and connect them in parallel. This permits the battery to float on the bus and thus automatically charge and discharge as the pressure rises above or falls below the normal. The effect of this is to steady the bus pressure greatly and to partially sustain it in case of interruption of the power supply.

Alternating Current Regulation. — In alternating current systems the control of the pressure is accomplished by the use of potential regulators placed on individual feeders, thus affording means of compensating for loss on feeders of different lengths and for the unbalanced load on the different phases of a polyphase circuit.

The primary (2300 volt) main system of adjacent feeders is not interconnected as are the mains of a low voltage network, and it is, therefore, not possible to get the benefit of equalization of loads which tends to give an even distribution of pressure. The pressure at the center of distribution is controlled by a potential regulator, and the primary mains radiating therefrom must then be arranged to keep the pressure drop as nearly alike on the various branches as possible.

Where the secondary (230 volt) main system is interconnected, there is a tendency to equalize loads between adjacent transformers, thus improving the distribution of the pressure at points which are at times heavily loaded.

With very large low-tension networks the conditions tend to approach those found in a large direct current network. The sizes of manhole transformers become so large that they have to be put into a building, and this necessitates the use of low-tension feeders. The feeders tend to be shorter, however, since the distance between transformer vaults is less than that between direct current substations. Pressure regulation may, therefore, often be taken care of at the vault or substation bus. Any feeders of great length may be readily controlled by the use of feeder regulators.

Bus-bar Regulation. — The automatic regulation of bus pressure is desirable where automatic feeder regulation is not used, as the operator can properly care for gradual changes in the feeder load by hand regulation, if the bus pressure is held steady by the automatic devices. It is also desirable in any case where a steady bus pressure is required.

The automatic regulator devised by Tirrill has proved very successful in the control of bus pressures. The general scheme of connections for this device is illustrated in Fig. 42, and the action may be described thus:

The secondary circuits of the potential and current transformers of the generator are led through a solenoid in a compounding relation. The current section is subdivided so that different rates of compounding may be secured. A movable plunger is actuated by this solenoid, which in turn actuates a counterweighted lever, the opposite end of which is equipped to make electrical contact in a relay circuit. The other con-

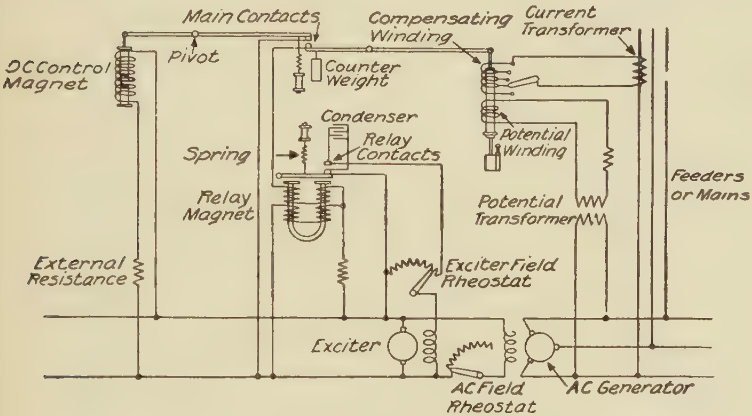


Fig. 42. Tirrill Regulator Connections.

tact terminal of this relay circuit is carried on a similar lever which is actuated by the plunger of a direct-current solenoid. This solenoid receives current in proportion to the pressure at the exciter terminals. The relation of these contact-making levers is such that increased pressure at the exciter brushes tends to open the relay circuit, while increased pressure at the main-generator terminals tends to close it. The closing of the relay circuit demagnetizes the relay as the other arm of the relay is continuously excited in the opposite sense. As soon as the poles of the relay are demagnetized its armature is withdrawn by a spring. This closes a circuit which shunts the field rheostat of the exciter and greatly increases its terminal pressure. This increases the pull of the direct-

current solenoid plunger and opens the relay circuit, thus weakening its pull. The result is a rapid vibratory action which is kept up almost continuously. As the load increases, the current winding on the alternating-current solenoid exerts an increased pull on the plunger which causes the lower contact of the relay circuit to move upward toward the other contact and thus close the relay circuit sooner. This raises the exciter pressure, and thereby the generator pressure, until it has been restored to normal. The vibratory action continues as before but the contacts are working in a slightly higher position in space, thus forming a "floating contact."

A condenser is used to diminish the action of the arc at the contact which shunts the exciter rheostat.

The ability of the shunt contacts to break the circuit is the limiting feature of the apparatus. This limit is reached at about 50 kw. on the exciter or 2000 kw. on the generator. Above this two or more breaks must be used in series, each shunting a portion of the exciter field rheostat.

Where there are several units in parallel in a station the regulator may be applied to the exciter for a part of them and the bus regulated for constant pressure, with the series coil of the alternating solenoid cut out. With this arrangement the bus pressure may be maintained constant at any desired point by the insertion of an adjustable resistance in the pressure circuit of the alternating solenoid.

Feeder Regulators. — The design of an efficient and practical form of feeder regulator is fortunately quite feasible, and there are two types in general use in America. Stillwell, in 1888, devised a transformer with a secondary winding tapped at intervals, the taps being brought out to a dial switch. By the motion of this dial switch handle, more or less of the secondary windings could be thrown in series with the feeder, thus raising or lowering the pressure. A reversing switch was

also provided by which the pressure of the regulating transformer could be opposed to the bus pressure if desired. This type is illustrated in Fig. 43.

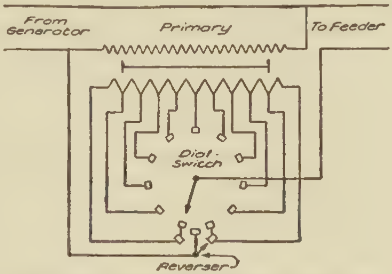


Fig. 43. Transformer-type Regulator Connections.

Another type of regulator which was developed somewhat later is known as the "induction" type.

In this regulator the variable voltage of the secondary is secured by turning the movable core on which the secondary is wound to different positions, thus linking more or less of the magnetic flux. If turned more than 180 degrees the secondary voltage is reversible through its full range.

This type is inferior in efficiency and power factor to the Stillwell type, owing to the presence of an air gap in the magnetic circuit, but its freedom from sliding contacts renders it more suitable for use in cases where remote or automatic control is employed. Fig. 44 illustrates a typical equipment of this class. In this installation the induction regulators are actuated by small three-phase motors mounted on the regulator frames. A reversing switch located on the feeder panel enables the operator to move the regulator in either direction, thus raising or lowering the pressure. A limit switch is provided for the purpose of cutting the motor out when the regulator has been brought around to the position of the maximum boost or choke. Hand control is also provided for use in emergency.

Automatic Regulation. — Automatic feeder regulation has been adopted quite generally in conjunction with the use of motor-operated regulators.

The use of automatic voltage control is essential to first

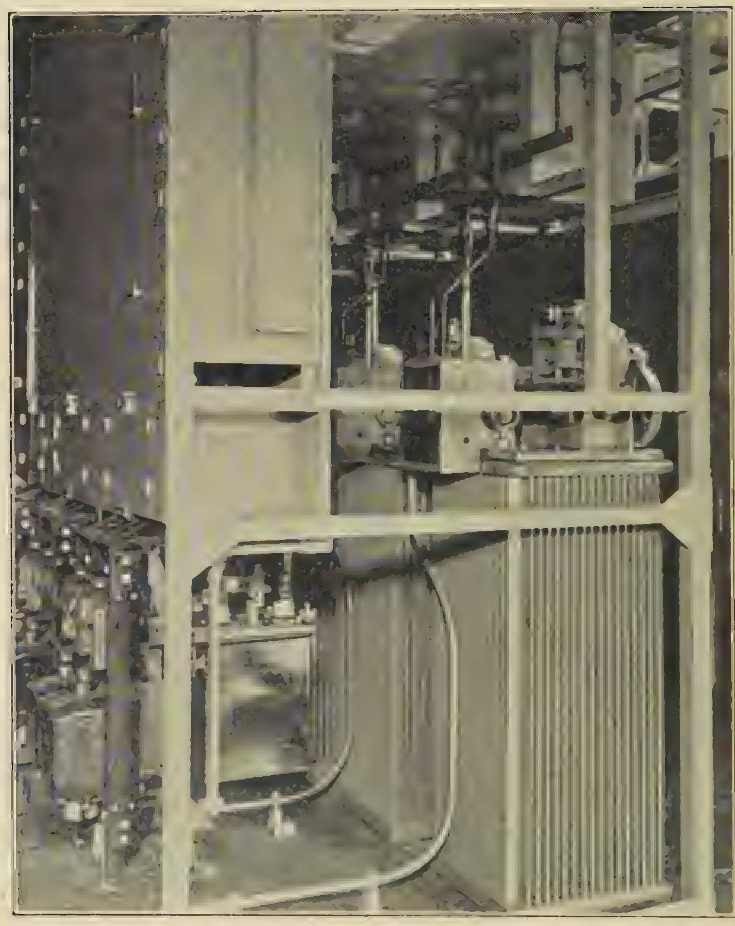


Fig 44. Automatic Induction Regulator.

class service where there are a number of circuits and where the duties of the operator make it impracticable for him to watch the pressure continuously.

This is particularly important with circuits having a mixed power and lighting load, which is continually varying as the power demands change.

The general use of automatic regulation has led to the development of automatic regulators designed for installation out of doors without attendance. These regulators find a special field of application in the supply of lighting service

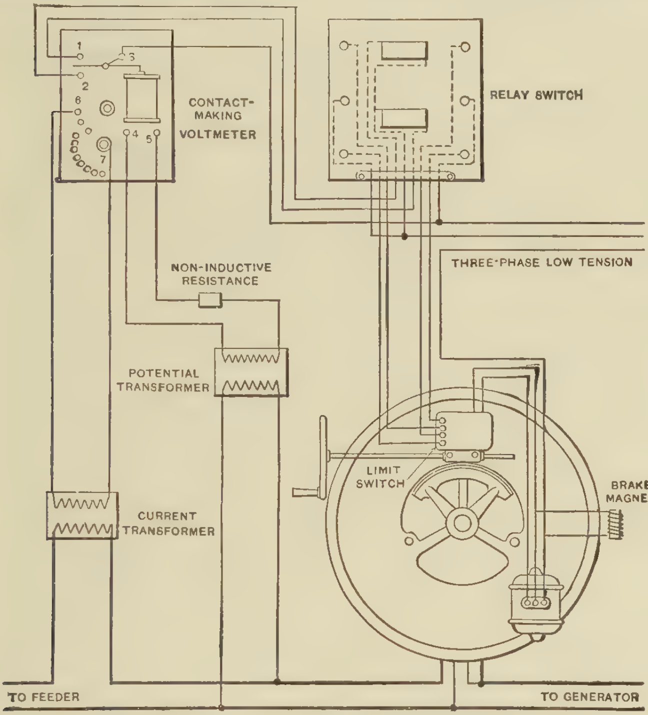


Fig. 45. Connections, Automatic Induction Regulator.

to towns and villages which are served from a transmission line by an out door substation.

The equipment often employed for automatically controlling the pressure on a feeder is shown in Fig. 45. This consists of a motor actuated potential regulator with limit switches to stop the motor when the regulator has reached the limit of its travel in either direction, a relay switch which controls the supply of energy to the driving motor, a contact-making

voltmeter, which is devised and adjusted in such a manner as to cause the relay switch to close the motor circuit in the proper direction to raise or lower the pressure, as may be necessary, and current and potential transformers, as indicated.

The contact-making voltmeter contains a solenoid wound as shown in Fig. 46, one coil being magnetized in proportion to the pressure on the line side of the potential regulator and the other in proportion to the load carried by the feeder.

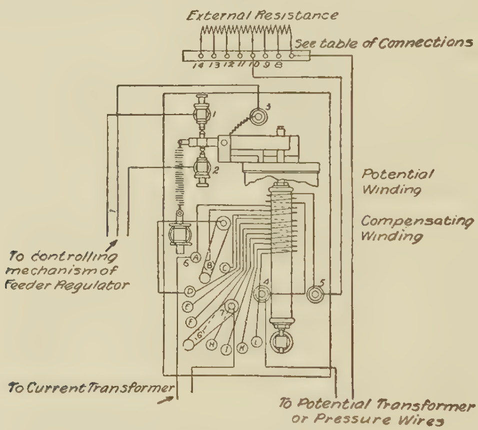


Fig. 46. Contact-Making Voltmeter.

This device thus serves the double purpose of compensator and voltage relay for circuits which do not require inductive compensation.

In this device, the constant pull, due to the standard feeder end pressure on the core is balanced against a spring. A series winding on the same solenoid carries current in proportion to the load on the feeder. The action of the series coils is opposed to that of the voltage coil and the result is that as more load is carried on the circuit, the pressure impressed upon the voltage coil must be increased in order to maintain a state of equilibrium on the contact-making lever. With

the proper number of series turns cut in, the pressure is automatically kept constant at the feeder end within 1 to 2 volts, at all loads.

The series coil is arranged in sections, two points being about 10 per cent each and eight points being about 1 per cent each. Thus the "contact making voltmeter" may be set to compensate for any feeder drop by steps of 1 per cent up to about 30 per cent.

The voltage coil in the contact making voltmeter is provided with an adjustable external resistance so that the device can be set for any desired standard pressure by steps of 5 volts. Intermediate adjustments are made by varying the tension on the spring against which the voltage is balanced.

With circuits whose load is so largely made up of lighting that their power factor is 90 per cent or higher, this form of compensator is found quite satisfactory and no separate line drop compensators are needed.

In manufacturing districts where feeders carry loads with power factors of 70 per cent to 80 per cent, the inductive drop on the circuit becomes a considerable factor and line drop compensators are usually provided where good service is required.

When compensators are used, the series coils on the contact making voltmeter are not employed, as the desired effect is produced upon the solenoid by the pressure coil alone, acting in conjunction with the opposing springs which control the contact lever. The pressure impressed upon the solenoid is compensated so that it represents the feeder end pressure. As this is to be kept constant, the spring may be set to offset a constant pull. When the feeder end pressure varies by 1 to 2 volts, or more, from the standard, contact is made by the levers, thus operating the regulator and restoring the pressure to normal. When the compensator is properly set,

the feeder end pressure is thus automatically maintained constant within a few volts.

The scheme of connections for automatic regulation with contact making voltmeters and line drop compensators is shown in Fig. 47.

The current from the secondary main current transformer of the circuit enters the compensator windings by way of the dial switch, and the voltage circuit is tapped at the points where the series coils are connected in the voltmeter type of compensator. The adjustment of the dial switch is made as in the voltmeter type. In case it is desired to maintain

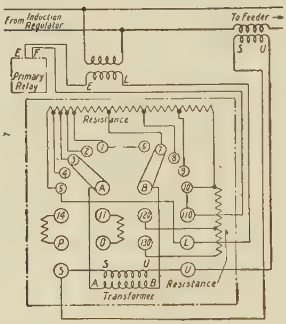


Fig. 47.

an indicating voltmeter in the circuit, as well as the voltage regulating coil, the voltmeter must be specially calibrated to correct for the constant drop in the compensator coils.

Line Drop Compensators. — The function of the line-drop compensator is to introduce into the feeder voltmeter circuit a counter E.M.F. which reduces the reading of the voltmeter by an amount equivalent to the line drop, and therefore indicates to the station operator the pressure delivered at the feeder end. The compensator circuit is a miniature of the feeder itself, the pressure transformer representing the bus bar, the compensator the line, and the voltmeter the load.

Since the feeder has both resistance and inductance, the compensator has two sections, one representing the ohmic and the other the inductive drop in the main circuit.

Each of these sections is provided with a dial switch, Fig. 48, by which sections may be cut in or out so that the compensator may be set to maintain a correct indication of the

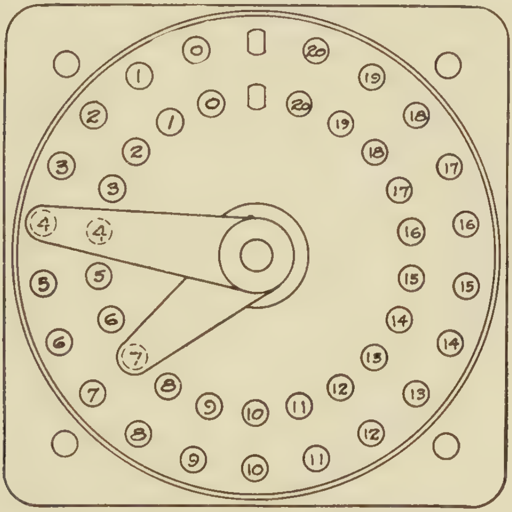


Fig. 48. Dial, Line Drop Compensator.

pressure at the end of a feeder at any power factor, or at any distance within its range of compensation.

Compensators are used with hand operated regulators in connection with an indicating voltmeter for the guidance of the operator, and with automatically controlled regulators with or without an indicating voltmeter. The indicating voltmeter is not required with automatic control under normal conditions as the operator depends entirely upon the automatic devices to keep the pressure normal. But in case part of the equipment becomes inoperative it is necessary to control the regulator manually and in this event it is neces-

sary to have a voltmeter accessible which can be connected to take the place of the equipment which is in trouble.

The general scheme of connections of the compensator, as worked out by the General Electric Company, is illustrated in Fig. 49.

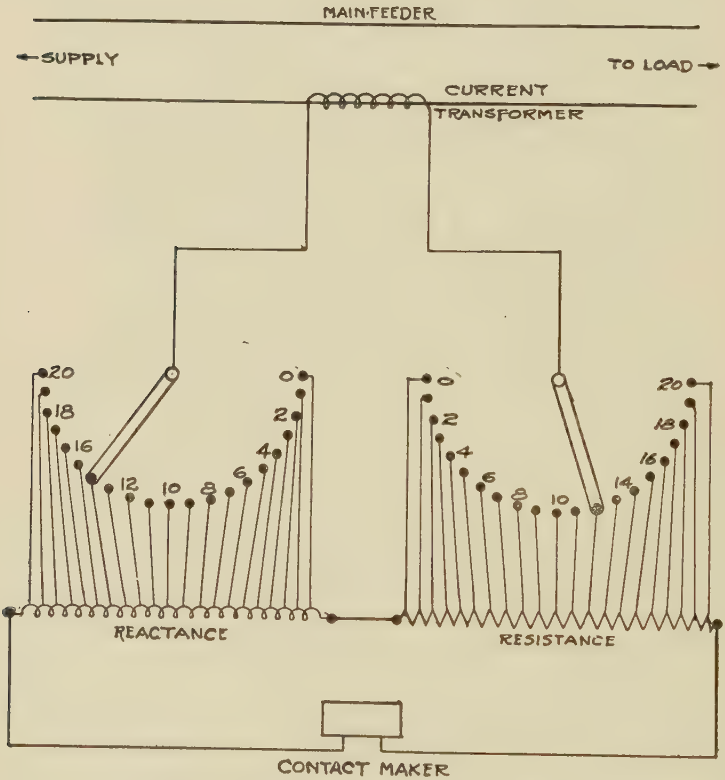


Fig. 49. Connections, Line Drop Compensator.

In this type the current from the main current transformer at maximum load is reduced from 5 amperes to 1 ampere by a current transformer inside the case of the compensator. There is a movable arm on each section and 20 points, each of which represents 1 volt when 1 ampere is flowing in the compensator.

The compensator shown in Fig. 49 is set so as to introduce in the voltmeter circuit an inductive counter E.M.F. of 14 volts and a noninductive counter E.M.F. of 12 volts when the feeder is carrying full load. The general appearance of this type is seen in Fig. 48.

Calculation of Compensator Settings. — With a feeder of No. 0 wire, 5000 feet long, single-phase, overhead wires 12 inches apart, pressure 2200 volts at feeder end, frequency 60 cycles, current transformer rated 100 to 5 amperes, pressure transformer rated 2200 to 110 volts, how should the compensator be set?

The full-load rating of the compensator being 5 amperes, that of the feeder is 100 amperes. The ohmic drop on a No. 0 feeder at 100 amperes is .2 volt per ampere per 100 feet of two-wire circuit. Hence the ohmic drop is $100 \times 5 \times .2 = 100$ volts, or 4.5 per cent. Likewise the inductive drop is .22 volt per ampere per 1000 feet, and the inductive drop on the feeder $100 \times 5 \times .22 = 110$ volts, or 5 per cent.

These values may be found for various sizes of wire in Table XXI, Chapter XVI.

If the primary mains are designed to give about 2 per cent ohmic drop, the transformers 2 per cent and secondary mains 2 per cent, the average ohmic drop from the feeder end to the consumer's premises would be about 3 per cent. The inductive drop would also be about 3 per cent. These average drops are applicable to the major portion of the distributing mains, and they may be added to the drop on the feeder and the compensator set so that the drop on both feeder and distributing system will be taken into account. The pressure may thus be regulated to give constant pressure at the average consumer's premises. In this case the total ohmic drop is $4.5 + 3 = 7.5$ per cent, while the inductive drop is $5 + 3 = 8$ per cent.

If a 20 volt compensator were used, the setting of the resistance section would be $7\frac{1}{2}$ per cent of 110, or 8 volts, and of the reactance section 8 per cent of 110, or 9 volts. The resistance arm would therefore be set at 8 and the reactance section 9. The operator keeps the feeder voltmeter at 110 volts at all loads, or at standard pressure, if that be some other pressure.

On a two-phase four-wire feeder the method of connection is similar to that used in the single-phase feeder, except that

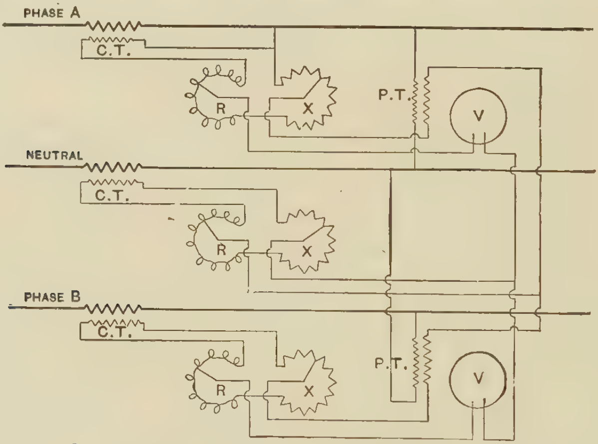


Fig. 50. Compensator Connections, Two-phase Three-wire Circuit.

one equipment is required for each phase. The method of calculating the setting for each phase is the same as in the case of a single-phase feeder. With a three-wire two-phase feeder, with unbalanced load one compensator is required in each of the three wires. The connections should be as shown in Fig. 50, when the load is unbalanced.

In calculating settings it must be borne in mind that the values of resistance and inductance per 1000 feet used in the case of a single-phase feeder are based on two wires, whereas in a three-wire feeder each compensator corrects the drop in one wire only. The values used for single-phase

feeder resistance must therefore be divided by two before being applied to a three-wire feeder whether two-phase or three-phase.

In case the common wire is equipped with a current transformer having a higher ratio than the other wires, or if the common wire is larger than the other wires, the proper values must be used for this conductor. The allowance made for drop in the primary mains, transformers, secondaries, etc., should be added to the calculation for the phase wires only of the feeder as it is in phase with the drop in these wires.

With a two-phase feeder of three # 0 wires similar in other respects to the single-phase feeder previously described, and with a current transformer in the middle wire rated at 150 to 5 amperes, the ohmic drop in the middle wire would be $5 \times 150 \times .1 = 75$ volts, or 3.5 per cent, and the inductive drop would be $5 \times 150 \times .11 = 82$ volts, or 4 per cent. The drop in the outer wires would be $5 \times 100 \times .1 = 50$ ohmic and 55 inductive, or about 2.5 per cent. Adding the allowance of 3 per cent for drop in the distributing mains, the compensator on the outer or phase wire should be set at 6 per cent on each dial of the compensator. The compensator on the middle wire should be set at 4 per cent on each dial.

In the case of a three-wire three-phase feeder, the connections of compensators and voltmeters are as illustrated in Fig. 51. It will be seen that the compensators are star-connected and the voltmeter transformers are delta-connected.

By this arrangement, the current in the compensators is brought into phase with the line pressure, since the current in the line wire is 30 degrees ahead of the line pressure, and with the secondaries of the current transformers in delta, the resultant current passing from them into the compensator is again thrown forward 30 degrees. This brings the current 180 degrees from the impressed pressure, when the load is approximately balanced on the three phases. The current

passing through the compensators is 1.73 times that in the series transformer coils and this must be allowed for in calculating the compensator settings as follows: If full-load current on a #0 feeder is 100 amperes, the ohmic drop per wire was found above to be $5 \times 100 \times .1 = 50$ volts at 5000 feet distance, and the inductive drop to be 55 volts. These

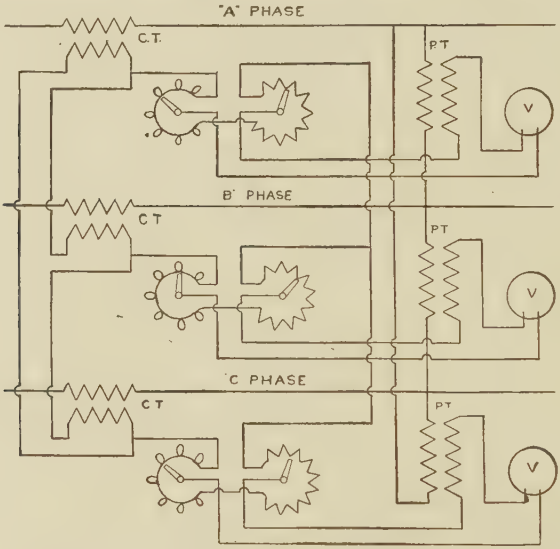


Fig. 51. Three-phase Three-wire Compensation, Star Connected.

values must be divided by 1.73 in order to derive a compensator setting which will be proportional to the current in the compensator coils.

When the current in the line is 100 amperes, the current in the compensator is not 5 amperes but $5 \times 1.73 = 8.66$ amperes. It therefore introduces a counter E.M.F. in the voltmeter circuit which is not proportional to the line drop, unless reduced by dividing the setting by 1.73. The ohmic setting in this case would therefore be $50/1.73 = 29$ volts, or 1.3 per cent, and the inductive setting would be $55/1.73 = 32$ volts, or 1.4 per cent.

This result may be secured by connecting each compensator into the secondary circuit of its corresponding line current transformer separately, and connecting the primaries of the potential transformers in star, as shown in Fig. 52. By this plan the potential transformers must have a 58 per cent tap on the primary winding, or special resistance coils in the voltmeter circuit, if standard 110 volt potential indicating instruments are used. This necessitates apparatus of non-standard

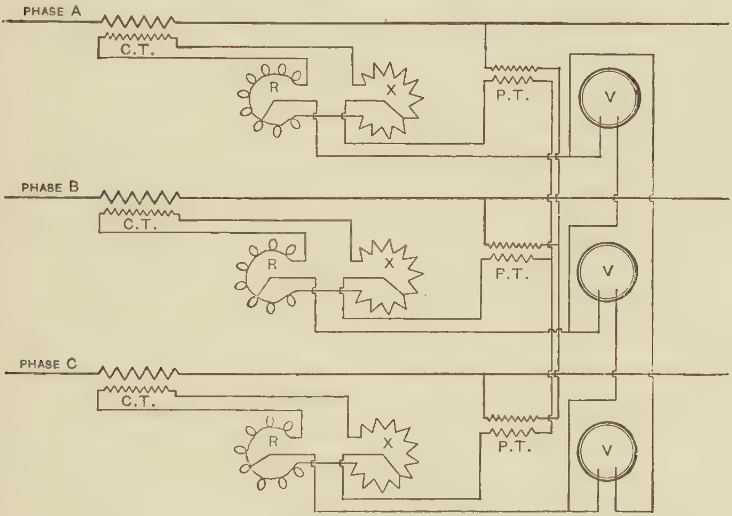


Fig. 52. Three-phase Three-wire Compensator, Delta Connected.

ratios, which is undesirable in the average installation, and the method by which the compensators are star-connected is usually considered preferable.

Where automatic regulation is employed, using devices such as the contact-making voltmeter, the pressure coils of the device are treated as voltmeters and the current coils as compensators in making up the diagram of connections.

The allowance for drop in distributing mains must be divided between any two compensators, as it is in phase with

the working pressure. 1 per cent should therefore be added to the 1.3 per cent ohmic and 1.4 per cent inductive drops, making the ohmic setting 2.3 per cent and that of the inductive 2.4 per cent.

In a three-phase four-wire system operating at 2200 volts between each phase and the neutral, the method of calculating the drop is as follows: With a feeder of four #0 wires running 5000 feet from the station as a three-phase feeder,

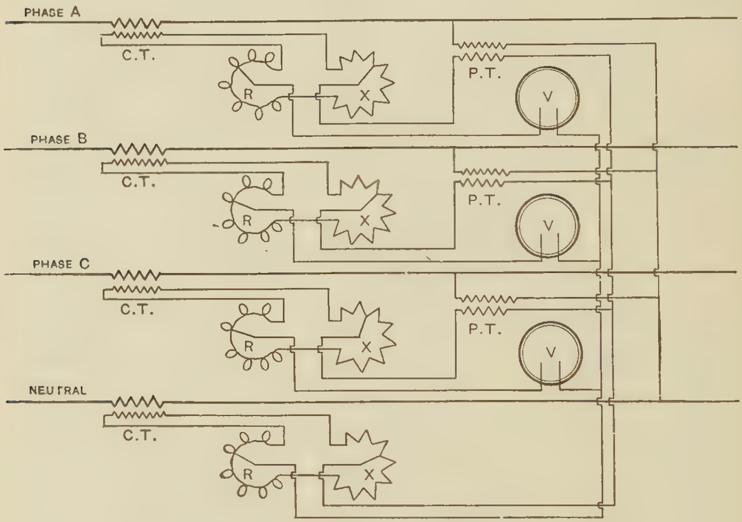


Fig. 53. Compensator Connections, Three-phase Four-wire Circuit.

the drop in each wire is 50 volts ohmic and 55 volts inductive. The working pressure being 2200, this is 2.5 per cent. If the entire load of the feeder is delivered from this center of distribution the compensator on each phase wire should be set at $2.5 + 3.0 = 5.5$, or say 6 per cent on each dial. That on the neutral should be set at 2 per cent on each dial. If, however, the A-phase branches off with a neutral to a single-phase center of distribution 2000 feet beyond, there must be added

to the A-phase setting $100 \times 2 \times .2 = 40$ volts $= 2$ per cent, making it 8 per cent on each branch. If the other phases branch to similar centers of distribution, at different distances, the drops must be figured as if they were single-phase feeders from the end of the three-phase transmission to the single-phase center of distribution. These drops must then be added to the three-phase drop above calculated. On four-wire 2300–4000 volt feeders which reach the limit of three-phase transmission within 3000 feet of the station, it is usually unnecessary to install a compensator on the neutral wires, as the neutral drop is negligible, even with a considerably unbalanced load.

The connections of compensators for a four-wire three-phase feeder are shown in Fig. 53.

Compensator Settings, Non-Inductive Type. — In making trial settings of the non-inductive type of compensators or of the General Electric contact-making voltmeter an allowance must be made for the effect of the inductive component of drop. Having calculated the ohmic and inductive component of drop, the impedance volts are the resultant of the two, $Z = \sqrt{R^2 + X^2}$. For the sizes and spacing of conductors usually found in distributing feeders the impedance may be considered as substantially equal to the actual drop at power factors of 85 per cent to 95 per cent.

For instance, with a #0 feeder carrying 100 amperes at a distance of 5000 feet under conditions as described previously the ohmic drop is 100 volts, or 4.5 per cent, and the inductive drop is 110 volts, or 5 per cent. The impedance is therefore $\sqrt{(100)^2 + (110)^2} = 148$ volts $= 6.7$ per cent.

If the resistance type of compensators were set at 6 per cent as a trial setting, it would be found to be very near the correct setting to give regulation within 1 per cent of the stand-

ard value at all loads. The contact-making voltmeter would be set in a similar manner.

The final adjustment should be made by comparison with 24-hour charts from a recording voltmeter at the feeder end with either of these types of apparatus.

CHAPTER V

LINE TRANSFORMERS

The transformer is perhaps, next to the generator, the most important piece of apparatus which the electrical engineer has at his disposal. Without it the development of alternating-current transmission and distribution systems would have been so greatly restricted that the use of electricity could never have reached the proportions of the present. Distribution would have been limited to lower voltages and transmission would not have passed beyond the limits within which generators and motors may be wound.

The transformer is the simplest piece of apparatus which is employed in electrical engineering. With no moving parts it is a mere combination of copper and iron which needs but the application of an electromotive force at its terminals to make it instantly operative.

The physical phenomena which take place in the transformer are, however, not as simple as its construction.

When pressure is applied to the terminals of the primary winding with the secondary circuit open, the current which flows is known as the leakage current. The leakage current is made up of two components, known as the magnetizing component and the iron loss component. The magnetizing component is that portion of the leakage current which induces a magnetic field in the iron core. The iron loss component is that portion which supplies the energy losses in the iron core.

The magnetizing component is a quarter cycle behind the impressed voltage wave, while the loss component is in phase

with it. The leakage current L is therefore $\sqrt{M^2 + I^2}$, in which I is the iron loss component and M is the magnetizing component. M is about twice as great as I in distribution transformers of 2 to 50 kw. capacity. The leakage current is readily determined from ammeter readings, while the iron loss may be found by the use of a suitable wattmeter. From these the magnetizing component may be readily calculated from $M = \sqrt{L^2 - I^2}$.

The secondary voltage is a quarter cycle behind the wave of core magnetism, which brings it a half cycle behind the primary impressed pressure, or in opposition to it. The ratio of the primary to the secondary voltage is called the ratio of transformation.

When current is permitted to flow in the secondary circuit, the magnetomotive force set up in the core causes current to flow in the primary of such strength that its magnetomotive force is equal to that set up by the secondary current. For instance with 100 amperes in a secondary having 100 turns, the magnetomotive force is 10,000 ampere turns. If the primary has 2000 turns the primary current will be such as to cause 10,000 ampere turns in it. The primary current will therefore be 5 amperes plus the leakage current when the secondary is delivering 100 amperes.

Ratio of Transformation. — The ratio of transformation of a transformer is fixed by the ratio of the number of turns in the primary to the number in the secondary. That is, a transformer receiving energy at 2000 volts and delivering it at 200 has ten times as many turns in series in its primary coils as there are in series in its secondary coils. When a transformer is wound with two or more sections in its primary or secondary coils, its ratio of transformation can be changed by changing the connections from series to parallel. For instance, in a 1100–2200 to 110–220 volt transformer, there

are four possible combinations of connections, viz., (*a*) primary and secondary sections both in parallel 1100 to 110 or 10 to 1, (*b*) primary in parallel, secondary in series 1100 to 220 or 5 to 1, (*c*) primary in series, secondary in multiple 2200 to 110 or 20 to 1 and (*d*) primary in series, secondary in series 2200 to 220 or 10 to 1.

The primary windings of line transformers are sometimes made so that they can be used on either 1100 or 2200 volt systems. The secondary windings of line transformers are divided so that they can be used in three-wire distribution in sizes above one kilowatt.

Transformers designed for transmission service are frequently made with several coils on both primary and secondary to permit their being connected in series for use on higher voltages later as the system develops.

The ratio of transformation is also sometimes made adjustable by steps of 5, 10 or 15 per cent, by bringing taps out from one of the windings of the transformer by which the pressure may be raised or lowered as conditions may require. Such taps are often specified in ordering transformers which are to be used where it is expected to raise or lower the transmission voltage later as the load changes.

The ratio of transformation expressed in terms of the ratio of the number of turns in the coils is strictly true only when the transformer is carrying no load. The resistance and inductance of the windings cause a reduction in pressure of 2 to 3 per cent when the transformer is carrying full load, thus modifying the ratio of transformation slightly.

Leakage Current. — The ratio of the number of turns in primary and secondary being fixed by the voltages of supply and delivery, it is necessary for the designer to fix the number of turns in one of the coils arbitrarily. This number must be high enough to furnish the magnetizing force for the core

without requiring too much leakage current. This leakage current in line transformers should not exceed 3 per cent of normal full-load current except in the smallest sizes, as there are many of them on a distributing system. The combined leakage current in a large system having a power factor of 50 to 60 per cent tends to interfere with the regulation of the generator pressure, and to increase the energy required for excitation of the fields during the hours of light load.

On the other hand, an increase in the number of turns requires a greater length of wire, which in turn tends to increase the cost of the transformer and reduce its efficiency. The number of turns must therefore be selected so that the leakage current and length of wire will be within proper limits.

Calculation of Windings. — The fundamental formula by which the induced voltage of a transformer is calculated illustrates these facts. The induced voltage of a transformer is $E = \dfrac{4.44\,fnF}{100{,}000{,}000}$, in which f is the frequency in cycles per second, n the number of turns in series in the coil and F the total magnetic flux in the core, at the maximum point of the wave. For 60 cycles and 2080 volts this becomes

$$2080 = \frac{4.44 \times 60 \times nF}{100{,}000{,}000}, \text{ or } nF = 781{,}000{,}000.$$

It is apparent that either the number of turns must be assumed to find the total flux, or the flux may be assumed to find the number of turns. The number of turns fixes the weight of copper and the copper loss, while the magnetic flux fixes the weight of iron and the iron loss.

It may seem at first sight that the area of the cross-section of the iron core would be about the same for all transformers designed for a given voltage without regard to size, since the

product of the turns and the flux is a constant which is fixed by the voltage.

However, the exciting current may be made proportional to the kilowatt capacity and this permits the number of turns to be reduced in the larger units, thus increasing the amount of iron in the core. For instance, in a 2-kw. transformer designed for 2080 volts there would be required about 1900 turns in the primary to keep the exciting current down to a proper amount. The total flux would therefore be $F = 781{,}000{,}000/1900 = 411{,}000$ lines. In a 20-kw. unit, the full-load current being ten times greater, the exciting current may be several times greater. Reducing the primary to 600 turns, the total flux will be $781{,}000{,}000/600 = 1{,}300{,}000$ lines. The average length of a turn is increased because of the greater cross-section of the core and the length of wire is therefore not reduced in proportion to the reduction in the number of turns. A number of trial calculations must be made with different ratios of turns to flux until the most economical combination is found for each size.

The total magnetic flux being determined, the area of the cross-section of the magnetic circuit is fixed by an arbitrary assumption of magnetic density per square inch. This value depends upon the character of the core material and may be varied 15 or 20 per cent from a mean value in order to produce consistent designs.

Iron Loss. — The iron loss varies as the 1.6 power of the magnetic density. The law governing this was discovered by Steinmetz and is

$$\text{Iron loss} = \frac{KfVB^{1.6}}{10{,}000{,}000},$$

in which f is the frequency, V the volume of the iron, B the number of lines per unit of area and K a constant depending on the kind of iron used.

It is evident from this formula that as the density is increased the core loss increases more rapidly. On the other hand, if the density is greatly decreased the weight of iron is increased and the cost goes up.

In the smaller sizes of 60-cycle transformers, where the weight of iron is small in proportion to the copper, the density is made lower so as to partly equalize this disparity. The iron in units of 1 to 5 kw. is operated at from 40,000 to 45,000 lines per square inch. In the larger sizes it is made 45,000 to 50,000, and in transmission units as high as 60,000 lines per square inch.

At 25 cycles the total flux for a given voltage must be greater and this tends to require greater cross-section. The iron loss, however, falls off with the frequency, and the density may be increased enough to make up for the decrease in loss at the low frequency. This permits the design of 25-cycle units at densities of 60,000 to 90,000 lines per square inch.

On the other hand, 125-cycle units are usually operated at 30,000 to 40,000 lines. The density having been assumed, the area of the core is $A = \frac{F}{B}$, or $\frac{1,300,000}{50,000} = 26$ square inches in a 20-kw. unit.

Magnetizing Current. — The magnetizing component of the leakage current for a given design may be computed from the formula $C = \frac{BL}{4.44\ NP}$, in which B is the number of lines of force per square inch, L the length of the magnetic circuit in inches, N the number of turns and P the permeability of the iron. Assuming a magnetic density, of 50,000 lines per square inch and a permeability of 2000, the magnetizing component of the leakage current would be

$$C = \frac{50,000 \times L}{4.44 \times 2000 \times N} = \frac{5.63\ L}{N},$$

or assuming the magnetizing current, the number of turns is

$$N = \frac{5.63\ L}{C}.$$

The number of primary turns and total flux of various sizes of 2200-volt distribution transformers are approximately as given in the following table:

Kw. Cap.	1	2	3	5	7.5	10	15	20	25	30	40	50
Mega lines	.26	.411	.550	.700	.88	1.02	1.2	1.35	1.45	1.53	1.7	1.85
Turns	3000	1900	1420	1100	890	780	650	580	550	510	460	420
Area of core ..	6.5	9.5	12.2	15.5	17.6	21	23.5	26	27	28	31	34

The formula $E = \frac{4.44\ nfF}{100,000,000}$ has been applied numerically in the foregoing only to units designed for 2080 volts and 60 cycles. It is apparent that for higher voltages the product nF will be proportionately higher and that more iron and copper will be required to construct a transformer of given capacity as the voltage is increased. Likewise, if the frequency is lower, the product nF is proportionately higher and more copper and iron are required to construct a transformer of given type and size in direct proportion. On this account 25-cycle transformers and induction motors require more material than the similar types of 60-cycle apparatus and cost more to build.

Types of Core. — There are two general types of arrangement of the windings and core of a transformer. One is known as the shell type, the other as the core type.

In the shell type the coils are threaded through the magnetic circuit and are surrounded by it, while in the core type the coils surround the core. The usual form taken by the shell type is that shown in Fig. 54. It has been used to some

extent in line transformers and very generally in connection with synchronous converters where air cooling is employed. The core type shown in Fig. 55 has been used very generally for line and transmission purposes where oil cooling is relied

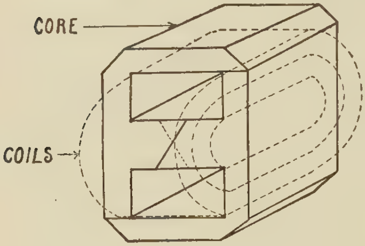


Fig. 54. Shell-type Transformer.

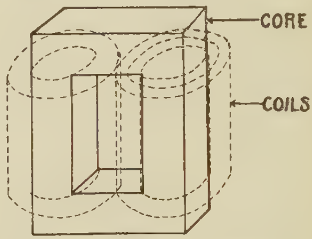


Fig. 55. Core-type Transformer.

upon. The cylindrical form of the coils lends itself to dissipation of heat and application of insulation more readily than the flat type of coil used in the shell type. The core type has therefore been used very generally for distribution purposes.

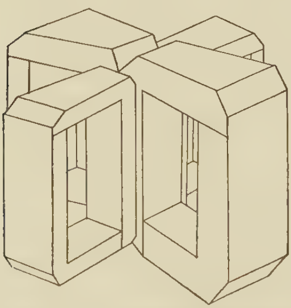


Fig. 56. Cruciform Shell-type Transformer.

In later years a modification of the shell type shown in Fig. 56, known as the cruciform type, was developed, which permits the retention of the cylindrical form of coil with the shell type of core. This form, which has been adopted by two leading American manufacturers, reduces magnetic leakage to a minimum, improves regulation and makes a very compact and efficient arrangement of copper and iron.

In the construction of the magnetic circuit of the transformer the iron must be in sheet form to reduce the flow of eddy currents which tend to be set by up alternating magnetic flux. The sheet iron is commonly about .012 inch thick, this thickness having been found to be the most effective

and economical. The shape of the stampings of sheet metal is carefully worked out so that they may be built up around the form-wound and insulated coils with facility. This must be done so as to affect the reluctance of the magnetic circuit as little as possible. The alternate laminations are therefore usually overlapped so that the magnetic lines of force do not have to cross a butt joint. The laminations are secured in position by bolts holding them rigidly in place.

Core Material. — The art of manufacturing sheet iron for use in making laminated magnetic circuits for alternating-current apparatus has made progress very steadily from the beginning of the industry. In the early years of alternating-current development the electrical manufacturer had nothing at his disposal in the way of sheet iron except the standard grades turned out for general purposes. It was found very soon that such iron when used in a transformer had magnetic properties which were variable with the length of time in service. The hysteresis loss per pound was high because of lack of proper annealing and varied widely in different lots because of the lack of uniformity in the heat treatment in the mill. The result was that a transformer which was reasonably efficient at the date of manufacture passed through a process of ageing which left it with a greatly increased hysteresis loss and reduced its all-day efficiency very materially. As soon as this phenomenon became well established, an endeavor was made to discover the cause of the ageing. The continued operation of the iron at higher than normal atmospheric temperatures seemed to be the seat of the trouble, and experiments were therefore directed along the line of careful control of the heat treatment of the sheet metal during the process of manufacture to insure as perfect annealing as possible in the finished product. The accumulated experience of years has produced gradual improvement in the magnetic

properties of sheet iron, though ageing has not been entirely eliminated in pure sheet iron.

The manufacture of sheet metal from an iron and silicon alloy has reached a stage where transformers are being manufactured with cores of this metal which not only permits the use of less core material but reduces the core loss and practically eliminates the ageing effect. Manufacturers of transformers have thus been able to reduce the cost of construction and produce more efficient apparatus.

The progress which has been made during the years 1900 to 1925 is made very plain by the diagram, Fig. 57, which shows the reduction of iron losses in the various sizes of line transformers during this period.

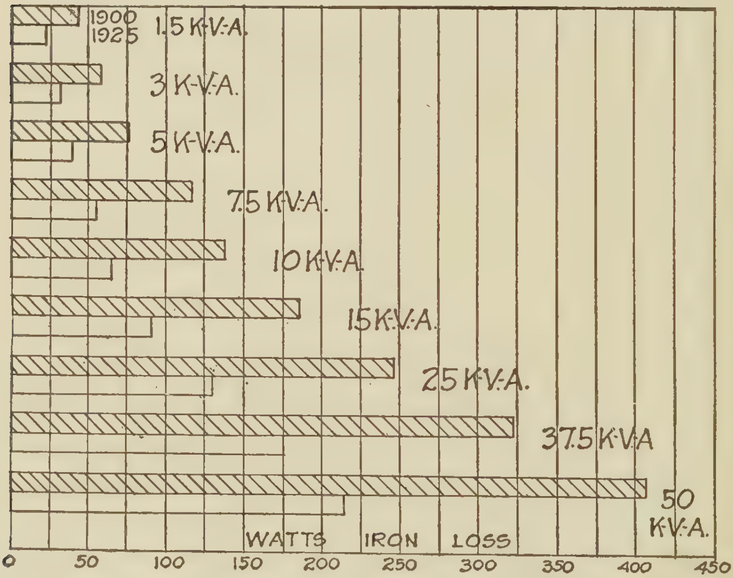


Fig. 57. Reduction of Transformer Iron Loss.

Copper Loss. — The loss resulting from the flow of current in the primary and secondary windings of the transformer is known as the copper loss.

It is the sum of the I^2R loss of primary and secondary coils when carrying full load.

The value of R for the respective coils is fixed by the length of the winding (number of turns $\times$ average length per turn) and the size of the conductor used.

For a given size of core the average length of a turn is determined and the size of the conductor is the only factor remaining to be selected. This is then so chosen as to make the value of R what it should be to give the desired copper loss.

In practical designs, the size of the copper usually works out about 500 circular mils per ampere at full load.

Relation between Iron and Copper Loss. — The ratio of iron loss to copper loss can be varied considerably without affecting the total loss appreciably. The iron loss, being continuous and constant as long as the rated pressure is applied, should be kept low, in order that the 24-hour loss may not be excessive.

The copper loss varies in proportion to the square of the current carried, and the total copper loss throughout a day or year depends upon the load factor of the energy delivered by the transformer.

Under the usual conditions of general light and power service, with load factors of 20 to 40 per cent, the copper loss should be higher than the iron loss at full load, in order that the total loss for a day may be a minimum. Thus, the loss in a 10 kw. transformer for a 24-hour day, in which it carries full load 8 hours, with iron loss at 65 watts and copper loss at full load (195 watts), is as follows:

$65 \times 24 = 1560$ watt-hours iron loss.
$195 \times 8 = 1560$ " " copper loss.

For higher or lower load factors the copper loss per day would vary proportionately.

The ratio of copper loss at full load to iron loss at full voltage is about 2.5 to 1 in sizes below 7.5 kv-a., and about 3.5 to 1 in the larger sizes up to 50 kv-a.

The relation of copper and iron loss is shown in the table following for sizes from 3 to 150 kv-a. inclusive.

DISTRIBUTION TRANSFORMER CHARACTERISTICS

Size Kv-a.	Watts Loss		Full Load Effic.	Regulation Per Cent	
	Iron	Copper 75° C.		P.F. 100	P.F. 80
1.5	23	47	95.6	2.35	3.3
3.	32	82	96.3	2.3	3.25
5.	40	108	97.1	2.25	3.15
7.5	54	150	97.1	2.22	3.1
10.	64	193	97.5	2.22	3.1
15.	90	263	97.7	1.95	3.05
25.	130	395	97.9	1.8	3.05
37.5	175	570	98.1	1.8	3.
50.	215	735	98.1	1.65	3.
75.	305	1175	98.1	1.65	3.
100.	420	1420	98.1	1.5	3.1
150.	630	2160	98.1	1.4	3.2

Heat Dissipation. — The problem of disposing of the heat generated in a transformer is one which has required a great amount of study and experiment. In the beginning of the art when units were small, natural radiation into the air was sufficient. As sizes increased this was inadequate to keep down interior temperatures to a point where deterioration of insulating materials would not take place. The air blast was naturally suggested as a means of hastening radiation and has found a useful field in stations and substations where attendance is continuous and floor space is limited.

This is not feasible, of course, for distribution work, and the use of a bath of oil around the coils was tried. This served the double purpose of excluding moisture and assisting radiation by the action of convection currents which cause the heated oil next to the coils to rise to the top, drawing the cool oil up from the bottom to take its place. This plan was soon

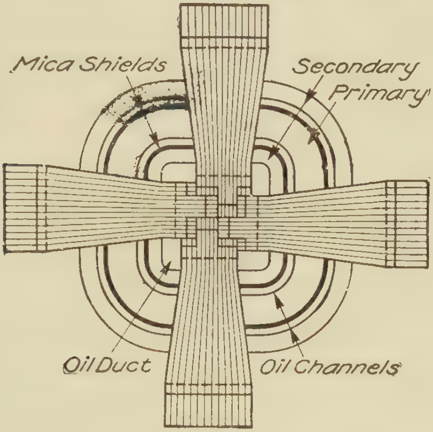


Fig. 58. Arrangement of Oil Ducts in Transformer.

found to be so effective both in cooling and insulating the coils that it became standard practice with all the principal manufacturers, and continues to be the method used for all line transformers and for station work where floor space is not limited or where the voltage of transmission is above 15,000.

In the design of the coils and cores of self-cooled oil-insulated transformers, it is important that they be so shaped and mounted on the core as to permit a free circulation of oil about them. For instance, in the core-type transformer the square corners are used in conjunction with the cylindrical coils to provide open vertical channels or flues through which streams of oil may pass, thus reaching the inner parts of the coils and core, and preventing these parts from reaching a

temperature very much higher than the outside parts as shown in Fig. 58.

In the shell type this is not feasible, and radiation must be accomplished by flaring apart the coils at the ends where they turn so that the oil can reach them on both sides and by providing circulation slots between the coils.

The radiation of heat from the case is facilitated by vertically corrugated surfaces which may be so designed as to greatly increase the radiating surface without increasing the cubic contents of the case.

Regulation. — The regulation of a transformer is dependent upon its ohmic resistance and its inductive reactance. Fortunately the size of the conductor required to keep the rise of temperature within safe limits is sufficient to keep the ohmic drop in the transformer down to a point which is satisfactory for general purposes. The fall of pressure in the transformer is fixed by the same principles which govern an alternating-current circuit. The resultant of the ohmic and inductive drops is the impedance drop, or $Z = \sqrt{R^2 + X^2}$, when Z is impedance drop, R is ohmic drop and X is inductive drop.

The impedance drop is, however, not the actual regulation of the transformer except at that power factor which is the same as the ratio of R to Z.

To determine the regulation at any power factor, the ohmic and reactance drops must be applied to the Mershon diagram. (See Chapter XVI.)

The reactance drop cannot be calculated directly, but may be determined by test as follows: With the secondary terminals of the transformer short-circuited through an ammeter the pressure on the primary terminals is brought up until full-load current passes through the secondary ammeter. The pressure required to do this is the impedance drop. The resistance drop of primary and secondary is found by passing

direct current through them and observing the voltage drop. The inductive drop is then found from the above formula $X = \sqrt{Z^2 - R^2}$.

Coil Insulation. — The insulation of the coils of a transformer from each other and from the case is of supreme importance. In transmission work large amounts of power are dependent upon the reliability of the transformer, while in distribution work not only the central station service but the safety of the general public is dependent upon it to a large extent.

The conductors are double cotton covered, to separate the adjacent turns, while the layers are separated by a proper thickness of varnished cambric, sheet mica or other insulating material. The completed coil is wrapped with linen tape covering the cotton braid, and impregnated with heated insulating compounds which drive off any remaining traces of moisture.

The primary and secondary coils being placed in close proximity are separated from each other by mica and hard wood or fiber so as to provide an oil-filled gap between the coils. The coils are likewise separated from the core by sheets of mica and other material. The cylindrical type of coils used in core-type construction and in the improved shell type are easily protected by layers of mica, and are therefore the most reliable form of coil for distribution purposes. Forms which require the protection of sharp corners are more difficult to insulate safely. Mica is not affected by heat or moisture and therefore forms the best insulating material where it can be applied effectively in sheets.

After being assembled on the core, the whole is impregnated with insulating compound by immersion in heated tanks under a vacuum. This eliminates all traces of moisture and entrained air from the coils.

Case. — Distribution transformers are commonly provided with rugged cast-iron or sheet-steel cases adapted to stand exposure to the weather and the rough handling incident to installation and removal. They must be oil-tight, as leakage is likely to result in claims for damages from property owners as well as very unsightly equipment. The cover is made removable for convenience in filling with oil and in changing

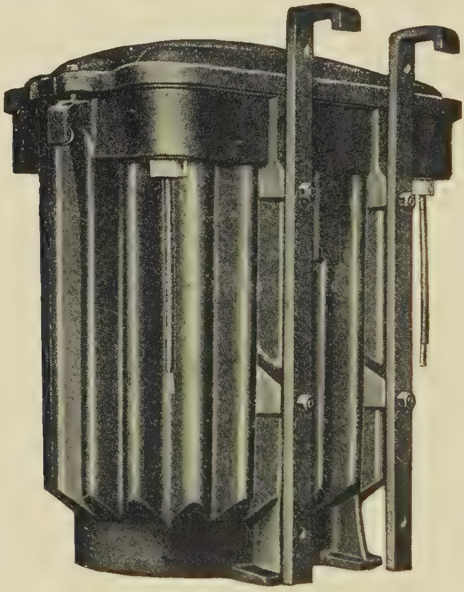


Fig. 59. Line Transformer Hangers.

the primary coil connections from series to multiple. Lugs are provided on the case to fit wrought-iron hangers by which they may be conveniently hung on a cross-arm, as shown in Fig. 59.

Polarity. — In connecting transformers in parallel, or in a 3-phase set, it is important that the polarity of the terminals be known.

The practice of marking transformer terminals in such a way as to indicate the sense of the winding has been standardized by the American Institute of Electrical Engineers, and the installation of connections for groups of transformers is greatly facilitated thereby. This may be better understood by reference to Fig. 60, showing the standard lettering used for this purpose.

These diagrams give a plan view of a transformer with high voltage terminals marked $H1$ and $H2$, and low voltage terminals marked $X1$ and $X2$.

When these are arranged in the same numerical order, $H1$ $H2$ and $X1$ $X2$, or $H2$ $H1$ and $X2$ $X1$, on each side of the unit, the polarity of each winding is the same. If either is in reverse order, $H2$ $H1$ and $X1$ $X2$, or $H1$ $H2$ and $X2$ $X1$, their polarities are opposite.

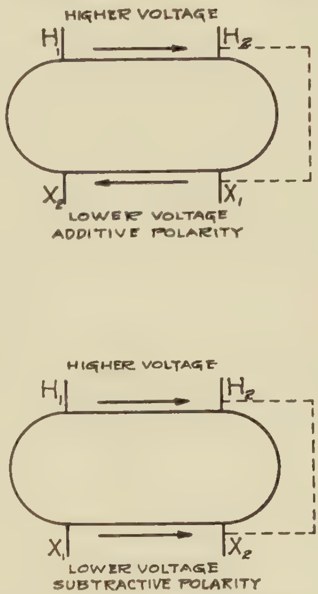


Fig. 60. Transformer Polarity.

The polarity is said to be "*subtractive*" when the 2 windings are in the same direction, and to be "*additive*" when in opposite directions. These terms arise from one of the methods of testing polarity. When one high voltage terminal is connected to the corresponding low voltage terminal, as $H2$ to $X2$, the resulting voltage on the terminals $H1$ $X1$, with either coil excited, will be the difference between the two coil voltages when the polarity is subtractive. It is additive when the resulting pressure is the sum of the two voltages.

The A.I.E.E. specifications recommend that the $H1$ termi-

nal be brought out at the right hand side of the case, when facing the high voltage side of the transformer.

Distribution transformers have been made for many years with additive polarity, while larger units have been made with subtractive polarity for the most part.

Subtractive polarity has some advantages for higher voltages, and has been standardized for large units.

In view of the large number of distribution transformers in service, the large users have preferred to continue to have distribution transformers made with additive polarity to avoid confusion.

Efficiency. — The physical laws governing the magnetic characteristics of a transformer having an iron core are fortunately such that the relative amount of copper required is

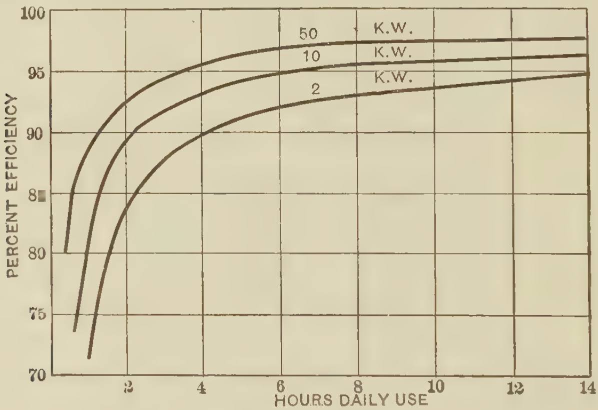


Fig. 61. All-day Efficiency of Transformers.

small, and the losses in the copper windings are not as great as they are in a generator or synchronous converter. The lack of moving parts further tends to make the transformer a most efficient piece of electrical apparatus.

The efficiency of a transformer which is used in transmission work is of most importance at the time of full load since it

usually carries its load several hours per day, and its iron losses are a small part of its converted output. It is important, therefore, that its copper losses be low and its full-load efficiency as high as possible. In a distribution transformer supplying its full lighting load but two to four hours per day, the full-load efficiency is less important, while the iron loss which goes on 24 hours may become a considerable percentage of the daily output of the unit.

The average values of efficiency, copper loss, iron loss and regulation of distribution transformers of the improved shell type made by the leading American manufacturers are shown in the table on page 134.

Three-phase Units. — In three-phase systems the possibility of saving a part of the core material and reducing the cubic feet occupied has led to the adoption of three-phase units in some kinds of work.

In the design of the core of three-phase units some saving in the weight of core metal is possible when the middle phase is connected in reversed order so that the magnetic fluxes of the adjacent phases do not combine in the usual 120 degrees relation but at 60 degrees apart.

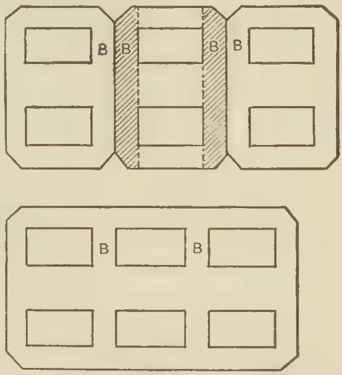


Fig. 62. Single and Three-phase Cores, Shell Type.

For instance, the shell type unit, as shown in Fig. 62, may be designed with the same cross-section at B as each of the three single-phase units has at the points B, thus saving the shaded portion of the middle single-phase core.

In underground work the saving in space is of value in a manhole, but the shape of the three-phase unit is such that

it cannot be installed or removed unless a special size manhole cover is used.

The three-phase unit has not, therefore, been generally used in distribution work, except where local conditions make it compulsory.

The three-phase unit as worked out in the core type with oil cooling is illustrated in Fig. 63. This type is used in distribution work or in situations where attendance is not con-

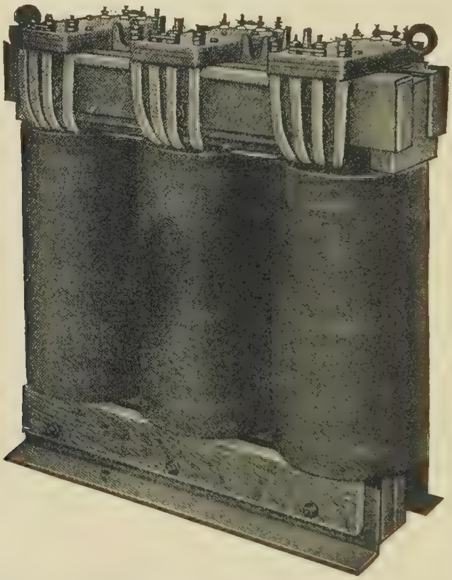


Fig. 63. Three-phase Oil-cooled Transformer.

tinuous. It is not usual to use a three-phase unit smaller than 15 kw. Having the three phases contained in one case they are made in larger capacities than single-phase units, having been made as large as 15,000 kv-a. for use in transmission work.

For general distribution purposes the three-phase unit has some serious limitations. It puts the entire load furnished by the unit out of service if any trouble develops in either

phase of the unit, and the expense of providing a substitute unit is necessarily greater.

Where transformers of all sizes must be kept on hand to take care of light and power service it is more flexible to have single-phase units which are available for either light or power than to attempt to carry a line of single-phase units for lighting and three-phase units for power.

CHAPTER VI

SECONDARY DISTRIBUTION

Historical. — In the early stages of the introduction of alternating-current systems the use of 55-volt secondary circuits was adopted in some systems because of the more rugged character of incandescent lamps of these voltages. Such voltage could be used in alternating-current systems because of the possibility of locating transformers close to the customer's premises. However, it was not possible to supply more consumers from one transformer than could be reached from the pole on which the transformer was placed without an excessive use of copper. The result was a system in which a large number of small transformers were required. These consumed an excessive amount of energy in their cores and required the operation of extra generating capacity at times to supply their large leakage currents.

As these distributing systems attained such size that these items became an appreciable expense, a remedy was sought. The higher voltage lamp having been improved, 110-volt secondaries were introduced and the 55-volt consumers were gradually changed over to 110 volts. The use of the higher voltage increased the range of distribution so that a single 110-volt transformer was installed to replace several 55-volt transformers, with a saving in the amount of capacity required and a very great reduction in the core losses and leakage currents.

Later the availability of the Edison three-wire system for general secondary distribution increased the range of such lines by permitting the use of 110–220-volt mains, with 110-volt lamps.

At this voltage, distribution may be economically made from transformers spaced 600 to 1000 feet apart. This greatly increases the number of consumers which can be supplied from a single unit, and permits a great saving in investment as well as in iron losses since the larger kilowatt capacity in a single unit costs less than the same capacity in several smaller units and requires much less energy to supply the iron losses. For instance, in replacing five 1-kw. units, with one 5-kw., there is a saving of about 50 per cent in investment and iron losses.

Furthermore the diversity of habits of use of electricity of a large number of consumers is such that the maximum demand on a transformer which covers 1000 feet of line is much less than would be the sum of the maxima of several units covering the same consumers. The advantage thus gained from what is known as the diversity factor often permits a saving of 40 to 60 per cent in the investment in transformers as compared with house-to-house transformers.

The three-wire 110–220-volt system is used for single-phase secondary distribution very generally in American cities, where there are a number of consumers grouped within economic range of a transformer. Two-wire distribution is used where consumers are few and scattered as in the early periods of development.

Periods of Development. — A system of secondary mains passes through three general periods of development in the growth of a city.

(1) A period in which scattered transformers supply isolated secondary mains not interconnected with other transformers.

(2) A period in which the mains from adjacent transformers grow together along principal thoroughfares where they may be connected to each other but intersecting few other secondary mains of importance.

(3) A final stage in which secondary mains are required generally and are therefore joined into a network.

The first period is that found in residence and other outlying territory not fully built up. When a new consumer is to be connected in such a territory the problem is — Shall a transformer be installed or shall the nearest secondary main be extended to the premises? The installation of a transformer involves an investment and an operating expense, due to its core loss. The extension of the nearest secondary main involves an investment in conductors and perhaps an increase in the capacity of an existing transformer. The cost of the two alternative plans being ascertained, the one selected should be that which involves the least annual cost for interest, depreciation and operation.

Example. — For instance, assume that service is required for a new consumer, with a load of 1 kw., at a point where there is no secondary main available. Also, that if a separate transformer is installed the investment will be about \$25, and if the nearest secondary main is extended the expenditure will amount to \$40. How shall service be given?

If the primary line is available and a new 1-kw. transformer is installed, the investment of \$25 will involve expense as follows:

15 per cent fixed charges on \$25	\$3.75
Core loss — 20 wts. × 8760 hrs. = 175 kw. hrs. at \$0.01	1.75
Total	\$5.50

If the secondary line is extended at an expense of \$40 (exclusive of poles), the fixed charges at 10 per cent are \$4 per year.

If the existing transformer has surplus capacity or if there is a considerable diversity factor between the new consumer's

load and the existing load so that its capacity is sufficient, the extension of the secondary from the existing transformer is the more economical procedure. But if 1 kw. capacity must be added to the existing transformer, this will add about \$10 to the investment and 10 watts to the core loss. The fixed charges are increased by \$1.50 and the energy loss by \$.87, making the total expense \$4.00 + \$1.50 + \$.87 = \$6.37, as compared with \$5.50 for the installation of a separate transformer. The new transformer would thus be preferable under this condition.

If the extension is being made at the end of the line where the primary does not extend beyond the last transformer, the extension of the secondary is usually preferable where small consumers are being added. This condition holds until distance becomes too great to give satisfactory service or the consumers become sufficiently numerous to warrant the installation of a transformer. In residential districts, it is possible at times to extend secondaries from 600 to 1000 feet in this manner.

There is little occasion in this period of development to connect secondary mains in multiple. Where the mains have been extended until they meet each other it is usually preferable not to interconnect them, as the blowing of the fuse of either transformer shifts the load to the other, and overloading it blows its fuse also; and transformers are so far apart that they cannot assist each other to any appreciable extent in case of an overload on either of them.

The second period of development is reached when consumers become so closely situated that it is necessary to provide a continuous secondary main along a thoroughfare. This condition is usually first met along business streets and boulevards, and results in a long secondary main fed at intervals by transformers but intersected by few other secondary mains of importance. When such a main has been established

the problem is to determine how far apart transformers should be located and what size of conductor should be used.

The density of the load varies in different parts of the street, and there are large blocks of load at particular points which make the problem a difficult one at best.

Assuming that electricity is to be distributed from a single-phase, three-wire, 115–230 volt secondary main, with an approximately uniform load density in each block, the best arrangement of transformer spacing and size of conductor will be that for which the sum of the fixed charges on transformers and line conductors and the annual cost of transformer iron losses is the least.

With transformer spacings shorter the size of the conductor required to give proper voltage drop and the load per transformer is smaller. As transformer spacings are increased the size of transformers becomes larger, but the cost per kv-a. of the transformer and its iron losses per kv-a. become less. The size and cost of the conductors are increased. Thus there are conflicting trends of cost which may be combined and plotted to ascertain the minimum annual cost.

Calculations of this kind made for the load densities commonly found in such cases may be found in the discussion of Economics of Distribution in Chapter XVI.

These determinations indicate that spacings of 400 to 500 feet are most economical, and this fortunately is about the length of city blocks, making it a good arrangement to provide one transformer installation per block. There is also a considerable range of spacings which are practically as economical as the minimum, which makes it desirable to provide conductor sizes which will allow for growth, and adjust transformer spacings as required when the location and amount of increased load are known. This permits the use of larger transformers and fewer of them in the earlier stages of development.

These determinations are based upon the assumption that the load is taken off with uniform density.

However, in practice, it is more often the case that certain portions of a secondary main are heavily loaded, while others carry a more scattered load owing to differences in the character of the neighborhoods which it serves. At occasional intervals department stores, churches or other large consumers of electricity throw heavy loads upon the line.

It is therefore necessary to locate transformers near to such large consumers' premises and to design the main between them to carry the scattered consumers whose load is distributed between. An extended secondary main may thus be made up of different sizes of wire in different parts with transformers having various spacings, depending upon the load density in the vicinity.

However, the design of those portions of a secondary main which serve the smaller consumers distributed along its route may be based upon the general theory outlined in the foregoing.

Networks. — The network is the last step in the development of a system of secondary mains. The gradual extension of mains on all intersecting streets results in a system of lines which is interconnected at intersecting points and thus becomes a network.

This condition is found chiefly in the central business districts of larger cities where buildings cover most of the frontage and there are retail stores, office buildings and other users of electricity in amounts sufficient to give load densities of 100 to 500 kw. or more per city block. In such districts the requirements of service are more exacting than in the less densely settled parts of the city, and more is demanded of the distribution system, in the following respects.

(*a*) The presence of theatres and large mercantile estab-

lishments where many people are assembled, demands that the system be *reliable*.

(*b*) The general use of lights and motors in practically all buildings requires that both light and power be supplied from the same system as far as it is practicable.

(*c*) The use of lighting service in offices, stores, and theatres requires that the lighting be steady and that the pressure be maintained during heavy load periods.

Reliability. — The high standard set by Edison direct current networks which, under storage battery protection, have in some cases had no general interruption of service for a decade or more, has not been equalled by any alternating current system. However, much has been done to improve alternating current distribution as the needs of cities have demanded it, and the stability of alternating current net works is, fortunately, materially improved as the density of load increases. With heavier load density, the average size of mains is increased and the network becomes so complete that energy is supplied to a short circuited transformer or cable main in sufficient amount to burn it clear or to blow its own fuses without blowing others and so spreading the trouble.

With a network supplied by low tension feeders from a well placed substation, and with equal load density, there is little difference between alternating and direct current as regards interruptions arising within the network. They are equally capable of giving an even distribution of pressure and of cutting out a faulty main through the operation of fused junction boxes.

When an alternating current network is supplied by high tension feeders, through primary mains and local transformers, the supply becomes distinctly less reliable than a purely low tension system because of the introduction of (*a*) transformers

and their fuses as a part of the distributing system and (*b*) a much larger unit of capacity in the feeder system.

The transformer itself is as reliable as the feeder and main system, but in such a system there are high tension cables, fuses and transformers between the source of supply and the low tension network, whereas, with the low tension feeders there are only low tension cables. Thus the chances of trouble are two to three times as great with high tension feeders and local transformers as with low tension feeders from substation to network.

The capacity of the feeder unit in a 230-volt system does not much exceed 300 kw., whereas, with high tension feeders it is 1000 to 2000 kw.

It is not a difficult matter to have reserve available in the network and feeder system to provide for the failure of a 300 kw. feeder, but special provisions must be made to maintain reserve for the loss of a feeder which normally carries 1000 to 2000 kw.

The practicability of any particular plan will be determined by the relative size of the system and the importance of the service.

Supply of Power Service from Networks. — Simplicity of construction and economy of investment are best secured when the network is capable of giving power as well as lighting service. This necessitates the use of a polyphase system, if there is any considerable percentage of power users of moderate size. Those requiring upward of 150 kv-a. are usually best served by a separate transformer installation in or near the premises, with a connection from the network as reserve for as much of the demand as may be so carried.

In a two-phase system the distribution may be effected by a three-wire Edison system from one phase for the lighting load, and a fourth wire for two-phase motor service, or it

may be a five-wire star-connected system, serving both light and power.

From a three-phase system, the light may also be carried on one phase with a three-wire Edison system, and a fourth wire for power service. Or it may be a star-connected, four-wire system with light and power on all phases.

The plan of carrying the lighting on one phase is useful in the earlier stages when load densities are not heavy enough to give a satisfactory balance of the load on all phases. This plan makes it necessary to balance the load on the primary feeder by having different sections of the lighting phase of the network on different phases of the feeder.

With heavier load densities the lighting is divided among three phases with the power on the same service connections, thus making a unified system for all general service, except very large users.

Lighting Service and Pressure Regulation in Networks. — The predominance of the lighting service in retail business districts, offices, and public buildings, is usually such as to permit the service of motor loads from the general network, though it is sometimes necessary to supply elevator service and other intermittent loads from a separate transformer installation.

With the increase of load density the distributing mains of the network become larger and the amount of starting current of motors becomes relatively a smaller proportion of the load and capacity of the mains.

When a network is so general as to cover all streets and give a number of paths for the flow of current from the sources of supply to the blocks of load, the pressure distribution tends to become more even, and the effect of a cable failure in a main less likely to be felt beyond the limits of the block in which the failure occurs.

The arrangement of a network served by transformers at street intersections is illustrated in Fig. 64.

The nature of the locality is often such that underground construction is required where a network exists. This necessitates manholes of ample size for transformers and such junction boxes as are necessary for the proper operation of the system. The space required is sometimes difficult to secure on account of gas and water pipes, car tracks and other

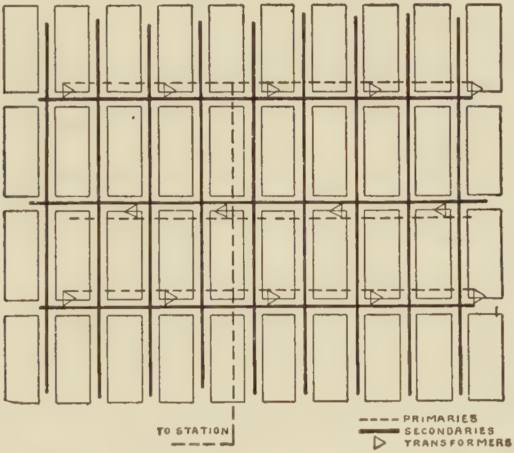


Fig. 64. Alternating-Current Secondary Network.

underground systems. It is not desirable to go below such obstructions, as the manhole should not be below the sewer level.

Where the load densities are such that transformers of 50 kw. and upward are required at the intersections, the problem of securing sufficient space for manholes of suitable size becomes increasingly difficult. In some cities, it is found practical to build vaults under the sidewalks, thus avoiding the piping systems in the streets.

In cases where there are alley lines intersecting secondary lines on streets, the manholes are placed at the alleys, thus

avoiding the congestion of underground structures at street intersections.

A further limitation of the size of transformer vaults in streets is found in the requirements for ventilation and heat dissipation. When manholes are in the street, ventilating facilities which will be adequate for large transformers are difficult to arrange and it may not be possible to prevent excessive temperatures at certain hours of the day.

These various difficulties have been sufficient in some cases to result in a decision to avoid the use of transformers in streets by distributing energy from low tension feeders and mains supplied by a transformer substation, centrally located.

Protection of Network Service. — The reliability of the service rendered from a network is largely determined by the means employed to isolate faulty parts of the system and the reserve capacity provided for use in such emergencies. The completeness of such protection is in turn dependent upon the permissible expenditure which may be justified by the service requirements and income derived.

Protective means are required for the three principal elements involved (assuming high tension supply); (*a*) the primary feeder and main system, (*b*) the transformers, and (*c*) the low tension network. Reserve facilities must also be provided in some form for each of these, for use in case of failure.

In the primary feeder and main system the protective equipment usually consists of an oil circuit breaker at the substation and either circuit breakers or primary fuses at the distributing transformers.

The transformers are protected by fuses and in some cases by " network protectors " or by reverse energy circuit breakers on the secondary side. The low tension network is protected by fused junction boxes as in a direct current system.

The reserve capacity may be provided in different ways which an assumed case may, perhaps, best illustrate.

The network of low tension mains shown in Fig. 64 is supplied by transformers at street intersections which in turn are

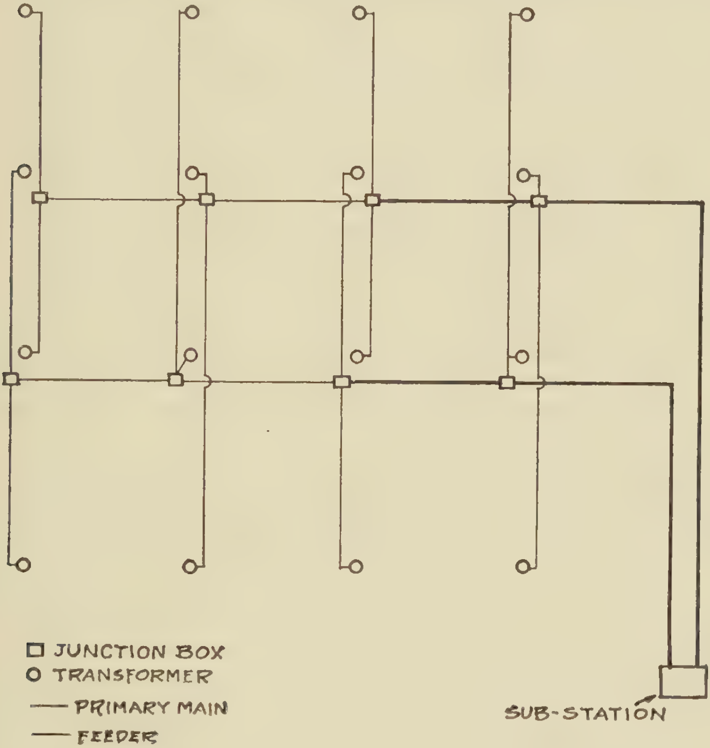


Fig. 65. Reserve Through Overlapping Mains.

supplied by primary feeders and mains. If the district were large enough to be supplied from more than one substation, it would be desirable to protect against a substation failure by having the feeders from the different substations overlap and thus not have any one section of the network dependent upon a single substation.

The illustration chosen is supplied from a single substation but the principle of overlapping is employed in the primary distribution mains as shown in Fig. 65, thus giving any part of the network support from more than one feeder.

In case of failure of a cable the circuit is disconnected at the substation by the circuit breakers. If the transformers are protected by fuses only, they will operate at the primary side of each of the eight transformers, and thereby throw all the load of the network to the eight transformers on the co-operating feeder. If only two feeders supply the network there should be about 100 per cent reserve in feeder and transformer capacity and the size of the low tension mains must be sufficient to carry the increased load near the transformers remaining in service.

If there are more than two feeders the reserve capacity is carried in the two or more feeders adjoining, thus reducing the percentage reserve to fifty or less. This is the condition commonly found in networks of larger cities.

Another method of supplying the load in an emergency is shown in Fig. 66. In this case the reserve in primary mains and transformers is 100 per cent as before, but the transformer capacity is provided in two units with one on each circuit, and this keeps the secondary system normal as regards points of supply and saves additional copper for reserve in the low tension mains. This plan has been adopted in some cases where the additional cost and losses incident to the use of two units at each junction was found less than the additional cost of secondary mains.

Another plan which has been used to some extent is to provide each transformer with two circuit breakers so relayed as to disconnect from the normal supply and connect to an adjoining feeder. By this plan the load may be distributed among several feeders or one spare feeder may be maintained as a reserve supply for two or three feeders. The

better plan is to have spare capacity in adjoining feeders as a rule.

This "throw-over" plan makes it unnecessary to subdivide the transformers or to provide surplus capacity in the low

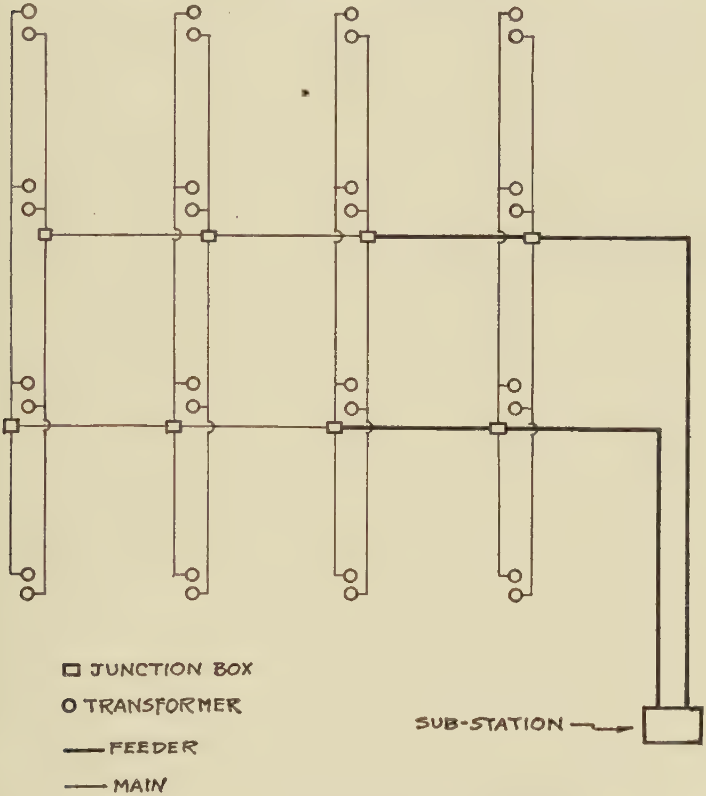


Fig. 66. Reserve Supply, Mains and Transformers.

tension system. The principal limitation of the plan is the space required for circuit breakers in vaults in public streets and the cost of installation.

Reverse energy circuit breakers on the low tension side of transformers, to disconnect them from the network, has been

found practical in some cases. In New York City a manhole type air circuit breaker of compact waterproof design has been worked out, which both disconnects the transformer from the network in case of reversal of energy flow into the transformer, and reconnects the transformer to the network when normal pressure is restored on the transformer. This serves to cut out a transformer or an entire feeder in case of trouble on the high tension cable system.

"Network Protector." — In systems which do not employ reverse energy circuit breakers on the secondary, the individual transformer is isolated in case it fails by the use of primary and secondary fuses. In many cases this has, however, resulted in drawing so much current from the network, momentarily, as to blow the fuses on other transformers and so spread the disturbance.

A special device known as a "network protector" has been devised to prevent such an occurrence, which has proved quite effective. The device is arranged on a differential principle which maintains a balance under normal conditions, but supplies a large flow of current instantly in case the balance is destroyed. This current flows through the normal fuses of the transformer and disconnects it more promptly than if the short circuit current were acting alone.

The arrangement of parts is indicated in Fig. 67. The protector has a winding in series with the high voltage side of the transformer and two other windings, one of which is in series with each half of the secondary of the transformer. The case chosen is that of a single phase unit with three-wire secondary.

Under normal conditions the currents in primary and secondary windings of the protector neutralize through its iron core and the protector has a very small effect on the pressure delivered by the transformer. When the transformer fails cur-

rent flows to it from both primary and secondary, setting up a current in the protector windings which is short circuited by the secondary fuses. These, and the primary fuses, are instantly ruptured and the transformer is cut out without disturbance to the remainder of the system.

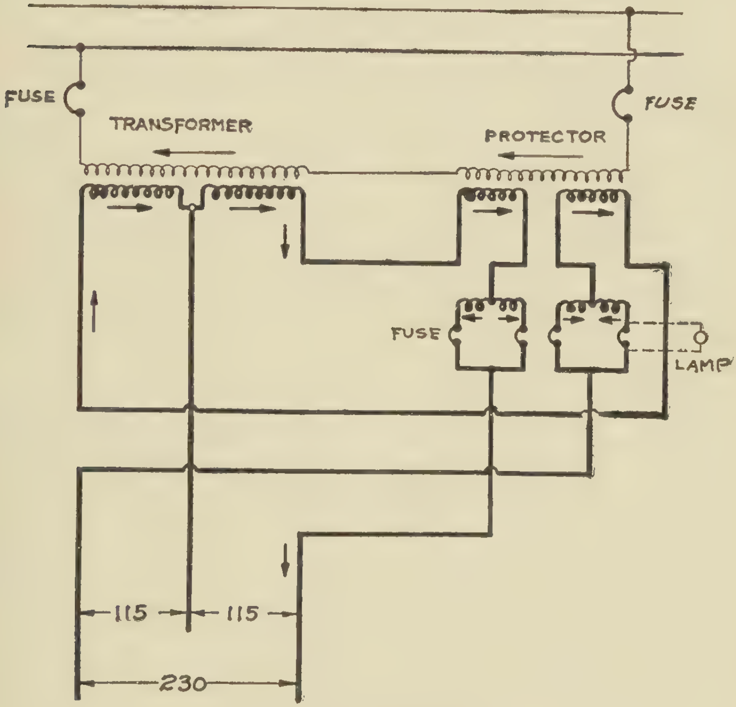


Fig. 67. Network Protection.

If a pilot lamp is connected across the secondary fuse, it will be lighted when the fuse is blown thus giving a visual indication of the fact that the unit is defective. This lamp may be located in a manhole or brought outside to a point of support from which it can be seen without opening a manhole, if desired.

Differential relay protection may be used to cut out trans-

formers in case of failure, where circuit breakers are provided on both primary and secondary sides of the transformer, but these require more space than is to be had in manholes in many localities.

Ring feeders, looped into each transformer vault, and having six to ten units per ring controlled by pilot wire and differential relays, may be found applicable in districts of high load density. This has the advantage of eliminating branch mains and avoids the necessity of duplicating the primary main system of adjacent feeders as is necessary with other methods described above. It is, however, limited by the space requirements of circuit breakers and is suitable only for relatively high load densities.

Two line circuit breakers and one transformer breaker are required in each transformer vault.

Network Supply from Low Tension Feeders. — The space required and the other practical difficulties arising in connection with the installation of large transformers and oil switches in public thoroughfares, increase rapidly with increasing load densities. The final solution of such problems must then be found in some plan which requires less space in streets and alleys. This may be accomplished by placing transformers in space within buildings or by establishing substations from which low tension feeders are run to junction points in the network or by a mixture of these plans.

The larger users (100 kw. and upward) may usually be best served from a vault in their premises with a service connection from the network as reserve against a transformer failure.

The smaller users are served from the network direct by low tension feeders from a substation within 1000 feet from the feeder end, as in a direct current system. This concentrates transformer capacity into a few large units with a

single high tension switching equipment which is less costly than the same equipment distributed in various places and largely, if not entirely, offsets the cost of the low tension feeders. The principal limitation of such a system is that the feeder cables must be of the multiple conductor type because of the losses in the lead sheath of single conductor cables of sizes above 300,000 c.m.

With the usual $3\frac{1}{2}$ inch duct system the largest size of three-conductor cable which can be used is about 700,000 c.m. with sector type conductors and 500-volt insulation. If the system is single phase, two-conductor cable of the " D " type may be used in sizes up to 1,000,000 c.m. or more.

The substations supplying such a feeder system are, of course, provided with reserve supply lines and all the protective facilities which are usual in substation installations.

Polyphase Networks. — As a network becomes larger and the load densities heavier, it becomes advantageous to use a polyphase system on the low tension network, and, except in a very few cities, this is a three-phase system.

In three-phase systems several methods of carrying mixed light and power load are in use. The most common consists of star-connected transformers supplying a four-wire main operated at about 115 volts from phase to neutral and 200 volts across phase wires. Lights are balanced as nearly as possible on the three phases. The smallest lighting services are two-wire, while larger ones are made three-wire, and connected to two phases and neutral and those of about 5 kw. or more are connected on three phases. Four-wire service is required for the larger users and in all cases where both light and power are to be served in the same building.

In another method, which is illustrated in Fig. 68, all the lighting is carried on one phase by means of a three-wire Edison secondary. Small power may then be served by the

installation of one additional smaller transformer and a fourth secondary wire. Larger power may require two power transformers in addition to the lighting transformer. The lighting in this system is easier to keep balanced, and since it is all on

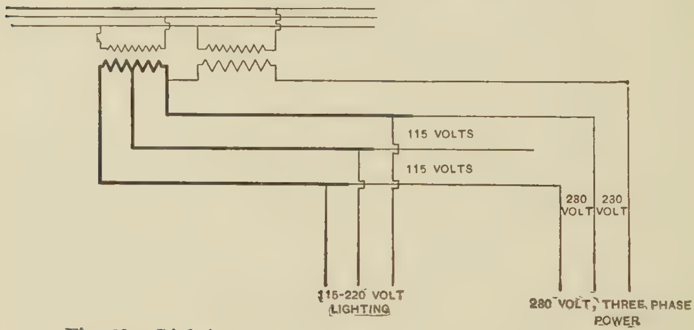


Fig. 68. Lighting on One Phase of Three-phase Secondary.

one phase the higher diversity factor requires less transformer capacity for lighting purposes. This reduces transformer investment and core loss materially as compared with the star-connected secondary, as the average size of the units is larger and the total capacity required is somewhat less.

Another advantage of carrying all lighting on one phase is that the effect of the starting current of motors is less noticeable on the lighting supplied by the large unit than it is where the starting current is drawn from three smaller transformers, each of which carries lighting load. It is therefore possible with this system to carry somewhat larger power loads on the same secondary main with the lighting than in the star-connected system under the same conditions.

When a network has been developed, this system cannot be interconnected with other secondary mains except those which are fed from the same primary phase. As the extent of the network increases this becomes undesirable and the objections to the star-connected system become less important. The four secondary conductors may then be changed

over to a star-connected system and the network may be interconnected throughout.

The use of combined light and power secondary mains becomes desirable in an underground system as soon as there is a sufficient number of power consumers to require a general system of power secondaries in any locality.

The expense of extra ducts and separate cables for separate power secondaries is excessive, and it is desirable to combine light and power secondaries into one system at an earlier stage of development than in the case of overhead lines.

Mains for Power Service. — The installation of separate transformers for power load necessitates separate secondary systems for power consumers whose premises are in the same vicinity. The design of such mains is governed by the same principles that control the arrangement of lighting mains, except that it is permissible to allow the secondary line drop to be 5 per cent or more instead of 2 to 3 per cent required for satisfactory incandescent lighting. This permits power secondary mains to be extended to about twice the permissible range for incandescent lighting. In manufacturing districts the power load usually exceeds the lighting, and duplicate secondary systems for light and power are often found. In residence and mercantile districts the reverse is the case, and the heavy lighting secondary system is capable of absorbing some miscellaneous power without seriously affecting the lighting service.

However, this is not desirable with the types of power which are intermittently used, such as coffee mills, meat grinders and other small apparatus which is used in retail stores.

The starting currents of these motors when wound for 110 volts range from 20 to 30 amperes or 10 to 15 times normal running. As the supply circuits are designed for the normal

running current, there is a pronounced drop in pressure at the instant they are switched on which produces flickering of lights. When the starting is frequent, this results in serious interference with lighting service, particularly in cases where retail stores are in or near residence districts. Relief can be secured in many cases by requiring motors which start frequently to be wound for 220 volts. In other cases a separate transformer is required.

Regulation of Transformers. — The regulation which will be secured with a given transformer may be calculated, if the impedance drop of the transformer is known. For instance, assume that a 10 kw. transformer wound for 2200–110 volts has an impedance drop of 80 volts or 3.6 per cent, also that the ohmic drop in the primary and secondary coils measured by means of direct current is 1.8 per cent or 40 volts, at full load. The reactance drop is

$$X = \sqrt{(80)^2 - (40)^2} = \sqrt{6400 - 1600} = 69 \text{ volts} = 3.1\%.$$

In Fig. 67 let OA be the impressed pressure on the primary at no load. AB is the ohmic drop in the transformer windings, which in this case is 40 volts. This is in opposition to the impressed e.m.f., and must therefore be added directly to it in determining what pressure must be impressed on the transformer in order to deliver its rated secondary pressure at full load. BC represents the inductive drop of 69 volts which must be laid off at right angles to AB. The pressure necessary to secure 110 at the secondary at full load is therefore $OC = \sqrt{(2240)^2 + (69)^2} = 2241$ volts. With an incandescent lamp load of 100 per cent power factor the regulation of this transformer is $2241 - 2200 = 41$ volts or 1.8 per cent.

With a load of 10 kilovolt amperes at 70 per cent power factor the regulation is calculated thus:

In Fig. 69 the impressed pressure 2200 volts at no load is OE. This is opposed by the power-consuming component of the load $OH = .7 \times 2200 = 1540$ volts, and the wattless component $EH = .71 \times 2200 = 1562$ volts. The ohmic drop in the transformer $EF = 40$ volts and the inductive drop $FG = 69$ volts. The impressed pressure at the primary necessary to maintain 110 volts at the secondary of the transformer is therefore

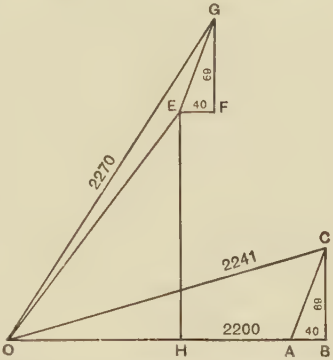


Fig. 69. Transformer Regulation, Inductive Load.

$$OG = \sqrt{(OH + EF)^2 + (EH + FG)^2},$$
$$OG = \sqrt{(1580)^2 + (1631)^2} = 2270 \text{ volts}.$$

The drop at 70 per cent power factor is 2270 − 2200 = 70 volts = 3.2 per cent. At 100 per cent overload this would be 6.4 per cent. With a motor taking two or three times full-load current at a power factor of 70 per cent or less at starting, it is evident that incandescent lights supplied by the same transformer will flicker whenever the motor is started and will burn at reduced candle power while the motor is running, unless the motor load is so small compared with the lighting that the starting current is less than the full-load current of the transformer.

With an inductive load, the power factor of which is 75 to 80 per cent, the drop at full load would be about 3.0 per cent. This would be considered too much for satisfactory incandescent lighting in many cases, and if so it would be necessary to set a separate transformer for the arc lamps. When combined with an equal amount of incandescent lighting, the resulting power factor at the transformer is increased

to about 95 per cent and the regulation of the transformer is within proper limits for satisfactory lighting.

Determination of Transformer Capacity. — The selection of the proper size of transformers for the supply of various classes of consumers is important since excess capacity involves idle investment and unnecessary core losses. The size of transformer units should therefore be kept as low as possible, consistent with preservation of the apparatus and good regulation.

Most electric light and power consumers do not use their entire connected load at any one time. There are always some lamps which are not in use at times when the principal part of the lighting is on, and in power installations the maximum load is usually less than the rated capacity of the motors.

Where a number of consumers are grouped on one transformer the maximum demands of the various consumers do not occur simultaneously and the resultant maximum demand is less than the sum of the individual demand. Measurements of demand may be made by means of an ammeter or by a Wright demand indicator. The use of the demand indicator is preferable as it may be left in circuit throughout any desired period and the maximum for the entire period thus determined. Certain demand factors may be established by a series of such measurements for the various classes of consumers for which it is necessary to select transformers. These factors may then be applied with reasonable accuracy to the selection of transformers for new consumers.

In store lighting the maximum demand for window lighting, signs and other display lighting is from 90 to 100 per cent of the load. The demand factor on interior store lighting is 50 to 70 per cent.

The demand of residences varies with the size of the house and with the number of persons living in it.

The demand of a single residence may, at times, be 60 per cent of the connected lighting load, with perhaps 30 per cent of the electrical appliance load on at the same time.

In the average house or apartment, in cities where the use of electrical appliances has been encouraged, the connected load in appliances is about equal to that in lighting. However, the electric iron, which is the largest consumer of electricity among appliances, is not in use while the percolator or toaster

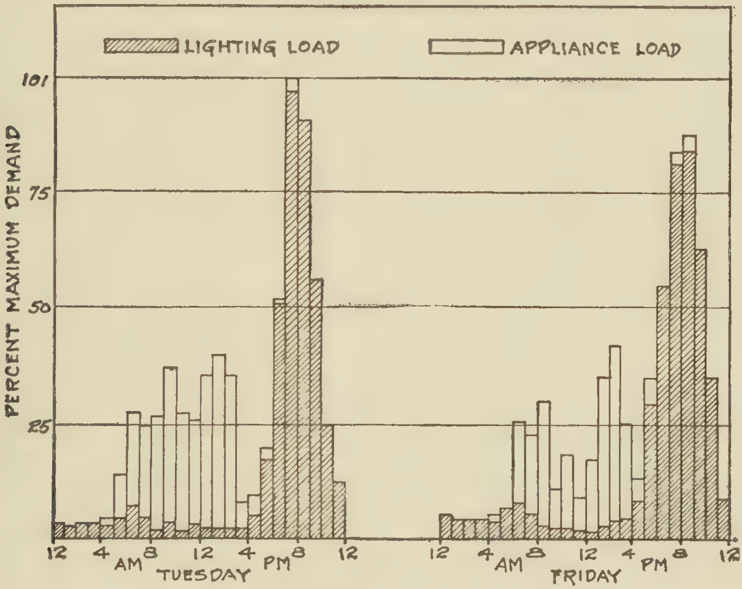


Fig. 70. Household Appliance and Residence Lighting Load.

are doing duty. The vacuum sweeper and washing machine also alternate with the iron.

Furthermore, most of these are put away for the day by the time the evening lighting load comes on, and the use of appliances adds but a small amount to the maximum demand of a group of residences. This is well illustrated by the chart, Fig. 70, which shows the use of electricity for lighting and

appliances on a Tuesday and a Friday in a spring month. This chart is based on tests made in 1922, in about 100 homes of different types, in 8 American cities, under the auspices of a Committee of the Association of Edison Illuminating Companies.

It is apparent that the appliance use at 7 P.M., when the use of lighting is greatest, is less than 5 per cent of the total demand and, thus, has a small effect on the transformer capacity required to serve such a group.

These houses had slightly more installed capacity in appliances than in lighting.

The demand made by groups of residences showed an increasing trend during the decade ending in 1925, due, in part, to the use of appliances, but much more to the increased standards of illumination, and the use of light for decorative purposes in the home.

Groups of houses and apartments in Chicago, which are served by a separate transformer and which have had no buildings added during a decade, show an increase of over 100 per cent in the group demand factor during that period.

The following data, relative to groups of this kind, are of interest in this connection.

Number and Kind of Users	Kw. Connected Light	Kw. Demand	Demand Factor
A 183 Apartments...........	132	37.0	28.0
B 190 Apartments, 3 Houses..	178	56.0	31.0
C 24 Houses (Small)........	26	6.0	21.5
D 18 Houses (Large)........	76	15.0	20.0

The demand of Group "B" was measured from time to time and increased from 26 Kw. to 56 Kw. in 10

years, though the number of users remained practically constant.

In each of the above groups the connected load in appliances is about 75 per cent of the lighting installation, except in Group " C," where it is 100 per cent.

In general a higher factor must be used where there are but two or three consumers on a transformer than where there are more, as the occasional maxima of individual consumers are a much larger percentage of the total.

In the case of churches and similar public buildings, capacity must be provided for the illumination of the largest room in the building together with the necessary hallways and corridors. This usually requires capacity for at least 60 to 75 per cent of the connected load.

In theater lighting the border and footlights of several colors are not used simultaneously and the stage and auditorium are not lighted simultaneously except for a very few minutes at a time. In a small theater the factor may be from 70 to 100 per cent while in a large theater it is frequently as low as 50 per cent.

Where several classes of buildings are fed by one transformer the capacity must, of course, be determined by taking each class into consideration separately and thus arriving at an average demand factor for the whole.

Power Service Demands.—The selection of transformers for power consumers is more difficult, as the maximum load may vary greatly from day to day or from month to month. The maximum load should be estimated where possible from the nature of the work done rather than from the motor rating, as motors are frequently chosen with reserve capacity. Elevator and crane motors require transformers of 100 to 125 per cent of their rated capacity unless there are several motors supplied by one unit. This is necessary in order to hold up

the pressure in starting. The load of such equipments is so intermittent that heating is usually not a factor in determining the size of the transformer.

The figures in the following table were made up from several thousand installations of direct-current motors in Chicago, which were equipped with maximum demand meters. They may be considered as representative, as they embrace every kind of manufacturing work which is commonly supplied by central station systems.

TABLE OF DEMAND FACTORS IN MOTOR SERVICE

Total installation in h.p.	Number of customers	Total h.p. connected	Average maximum h.p.	Ratio of maximum to conn. h.p.
1 motor,				
1 to 5	1177	2165	1862	86.1
6 to 10	124	1036	676	65.3
11 to 20	32	492	303	61.6
above 20	17	686	366	53.2
Total	1350	4379	3207	73.3
2 motors,				
1 to 5	177	412	285	69.1
6 to 10	51	387	261	67.4
11 to 20	30	438	288	65.9
above 20	6	203	74	36.5
Total	264	1440	908	63.0
3 to 5 motors,				
1 to 5	150	381	314	82.5
6 to 10	42	290	238	82.1
11 to 20	33	475	329	69.3
above 20	14	1245	657	52.7
Total	239	2391	1538	64.3
6 to 10 motors,				
1 to 5	42	121	80	66.0
6 to 10	21	157	98	62.4
11 to 20	10	155	98	63.1
above 20	19	931	417	44.7
Total	92	1364	693	50.8

Loading Distribution Transformers. — The permissible maximum load placed on transformers varies with the characteristics of the load curve of the consumers served. Power

service which is steady and continues from 6 to 10 hours per day must be supplied from transformers having a kv-a. capacity approximately equal to that of the load, since the transformer reaches its full temperature rise in 5 to 6 hours at a given load. But with lighting load, the peak period being usually not in excess of three hours, it is quite possible

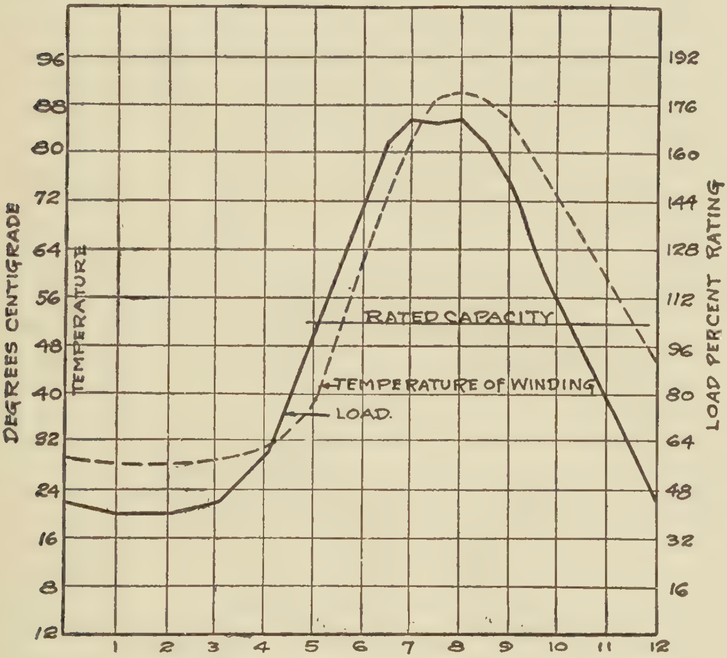


Fig. 71. Heating of Transformers under Overload.

to carry overloads during the peak period, without exceeding a safe temperature in the coils.

Tests made by different observers with characteristic lighting load curves show that it is possible to allow overloads of 50 to 75 per cent for a 2-hour period if the load decreases thereafter rather rapidly.

The curve of temperature rise follows an hour or more

after the curve of load increase and reaches its peak after the load has begun to go down. This relation is seen in the curves in Fig. 71.

The permissible overloading varies somewhat with different types of transformers, being affected by the freedom of oil circulation, the relative quantity of oil for a given size and the radiating surface of the case. A larger volume of oil per kv-a. tends to increase the overload capacity by increasing the heat storage capacity of the unit and the radiating surface.

The maximum temperature reached in the coils of a transformer, of course, varies with the temperature of the air, and this permits higher loading during winter months than during the warmer months of the year.

The results of tests indicate that a transformer which can be overloaded 50 per cent at summer temperatures can be overloaded 75 per cent in January and February, in latitudes where temperatures run below 0° C. in those months.

Efforts have been made to develop overload indicators operated on the general principle that when the temperature of the oil reaches or exceeds a predetermined value an indicator is operated, which is visible outside the transformer case.

There has been difficulty in getting a device which would be dependable and easily seen on pole transformers without climbing the pole.

In some cases, users of such devices have found it possible to materially increase the loading of their line transformers because of temperature indications so secured.

CHAPTER VII

SCHEMES OF TRANSFORMATION

Transformer Connections. — The connections of standard line transformers are shown in Fig. 72 for convenient reference. These transformers are usually made with two secondary coils, which may be connected for 110 volts to supply

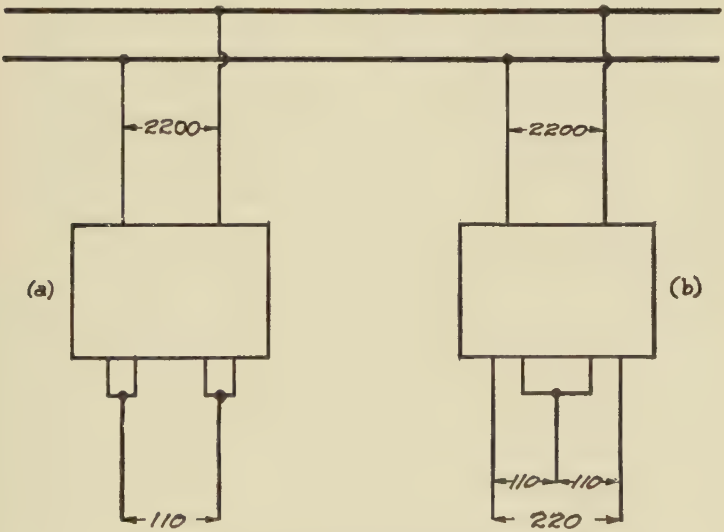


Fig. 72. Standard Transformer Connections.

lighting or power on the two-wire system, as in Fig. 72 (*a*), or for lighting or power on the three-wire Edison system at 110–220 volts, as in Fig. 72 (*b*).

Some systems operating at approximately 2080 volts use a standard transformer having windings for 1040–2080 to 115–230 volts, making a ratio of approximately 9 or 18 to 1.

The terminals of the secondary coils are brought outside the case in such proximity that they are readily put in parallel by joining the adjacent terminals. For 110–220-volt operation the two middle terminals are connected together, this forming the neutral of the three-wire system.

Standard three-phase connection diagrams are shown in Fig. 73 for delta connections, in Fig. 74 for Y connections,

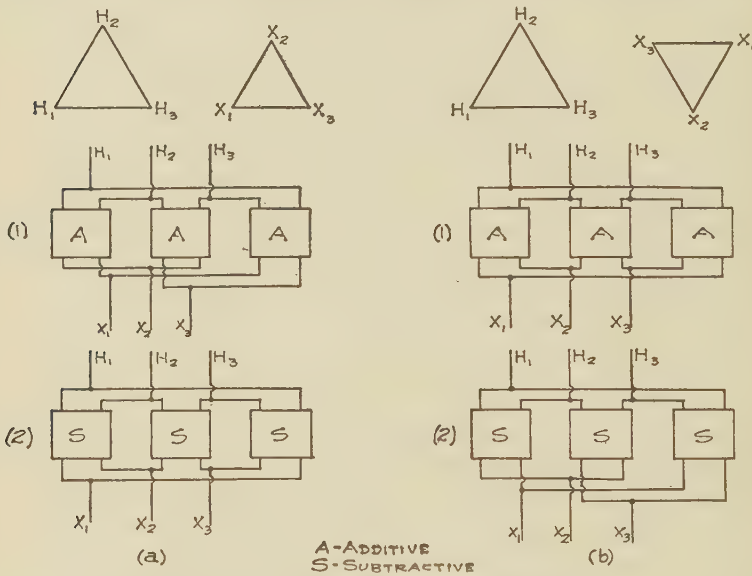


Fig. 73. Delta-Delta Transformer Connections.

and in Fig. 75 for two combinations of delta and Y connections.

The delta connection, so called because of the resemblance of the voltage triangle to the Greek letter delta, is used for 220-volt power service, for 2200-volt, three-wire distribution, and in many transmission systems.

The connections shown in Fig. 73 (*a*) are those in which the secondary voltages are in phase with the primary. This may be the case with windings of either additive or subtractive

polarity with the schemes of connection shown. In Fig. 73 (*b*) the secondary voltages are 180 degrees from those of the primary.

Additive polarities are standard with distribution trans-

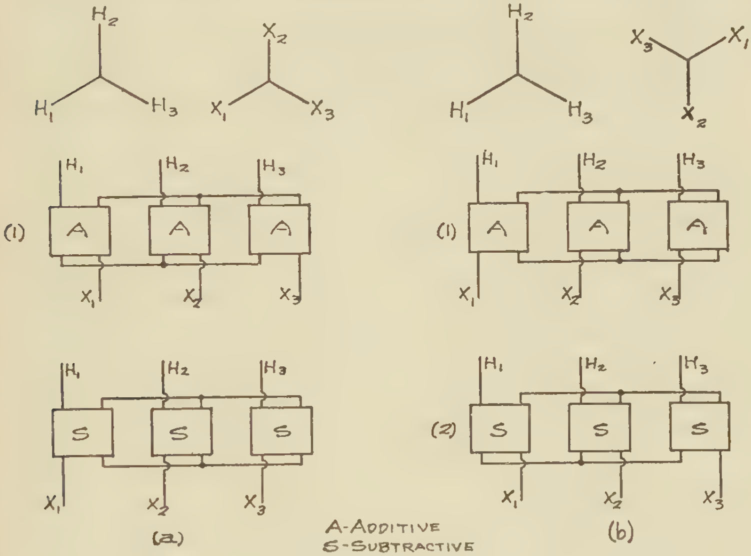


Fig. 74. Y-Y Transformer Connections.

formers up to 200 kv-a. capacity while subtractive polarities are standard in larger sizes.

The connections in Fig. 74 are known as Y-Y, from the resemblance of the voltage diagram to the letter Y. The use of the Y connection on both sides of a transformer is limited in practice to special cases, since this connection affords opportunity for the flow of harmonic currents in the transformer and its circuit. These tend to cause heating and may set up interference with communication circuits. The Y-delta or delta-Y connection shown in Fig. 75 is, therefore, commonly used where there are four-wire circuits requiring the use of a neutral conductor for distribution or for grounding purposes.

In special cases where, because of two successive transformations, it becomes necessary to use a Y-Y connection it is usual to provide a tertiary winding on the transformer core, which is delta-connected and acts as a damper for harmonic currents which may tend to flow.

In four-wire, three-phase distribution the primary distribution in cities is at 2300 volts from phase to neutral and

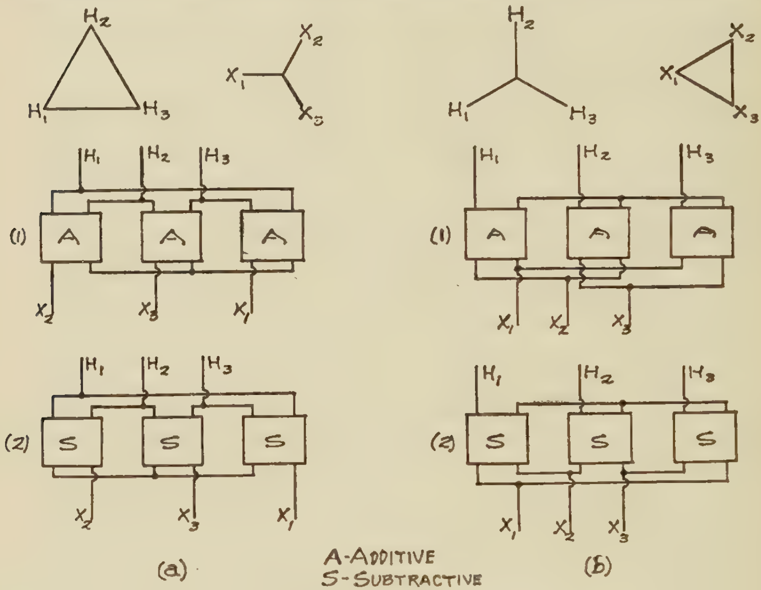


Fig. 75. Delta-Y Transformer Connections.

4000 volts between phases, the transformers being 2200-volt units Y connected.

In rural distribution, there is extended use of 4600-volt transformers on 4600–8000-volt circuits and 6900-volt transformers on 6900–11,000-volt circuits.

On secondary distribution, the delta connection at 220 or 440 volts is commonly used for power service from Y connected primary windings.

Where light is carried on one phase only of a secondary with power on the other two phases, the delta connection is used. In some cases combined light and power service are distributed from a Y connected secondary on the four-wire system with 115 volts from phase to neutral for lighting and 200 volts between phases. In a similar way light and power may be distributed in an industrial plant at 230–400 volts.

Booster Transformers. — Where it is necessary to raise or lower pressure when line drop is excessive, this may be accomplished in steps of 5 per cent or 10 per cent by a transformer used as a booster, that is, a transformer so connected that the secondary is in series with the primary main line. This raises the primary pressure by the amount of the secondary voltage, thus boosting the pressure of the circuit, as shown in Fig. 76.

For instance on a long, single-phase 2080-volt lighting branch which has so much load that the pressure drop is more than the normal regulation of the feeder will care for, a 110-volt transformer inserted in the line as a booster will raise the primary pressure 110 volts. This raises the secondary pressure 5.5 volts on all the transformers beyond the booster.

This increase in pressure is independent of the load carried by the circuit and therefore the pressure is maintained at a point about 5 per cent above normal during the hours when the load is small. If 10 per cent or more is added to the line pressure by boosters it is therefore desirable to arrange the booster, if possible, so that it can be switched out during the period when the load is small. This may be done by using a separate transformer for each step of 5 per cent.

It is desirable to place boosters as near the source of supply as possible, since the booster adds 5 per cent or 10 per cent, as

the case may be, to the current drawn by the branch of the circuit in which it is connected, and this increases the line drop proportionately.

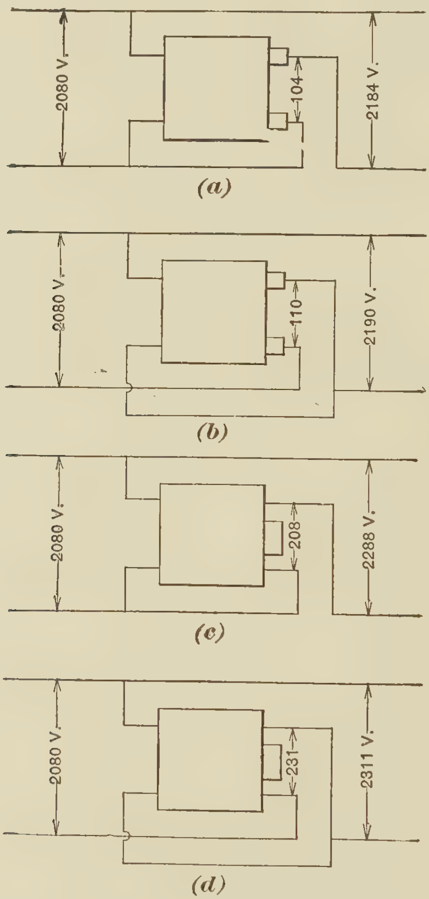


Fig. 76. Booster Transformer Connections.

The size of the transformer used as a booster must be such that its secondary coils may safely carry the full-load current on the primary main. In general, if the transformer

is to be used as a 5 per cent booster, it must have a capacity of at least 5 per cent of the maximum load on the main line, and if it is to boost 10 per cent, it must be able to carry 10 per cent of the load, etc.

With the secondary reversed the transformer becomes a choke, depressing the line pressure instead of raising it. This is a useful device in some schemes of connection, where less pressure is desired.

The proper connection of the secondary for booster or choke must usually be determined by trial for any given type of transformer. The connections of Fig. 76 are those for the transformers of additive polarity.

The connections for a single phase booster are made as shown in Fig. 76 (*a*), the line pressure being raised from 2080 to 2184 volts, or 5 per cent. The connection in (*b*) is that for an augmented booster, in which the line pressure is raised from 2080 to 2190, because the primary of the booster is connected across the line on the far side, and the booster is boosted as well as the line. This gives an increase of 5.5 per cent in the line pressure.

Fig. 76 (*c*) shows 10 per cent simple booster and (*d*) an augmented 11.1 per cent booster.

The corresponding connections for a 5 per cent choke are shown in Fig. 77 (*a*), a 4.75 per cent choke in (*b*), a 10 per cent choke in (*c*) and a 9.1 per cent choke in (*d*).

It should be noted that the transformers used in these illustrations have an interchangeable 10 or 20 to 1 ratio of transformation, and that these percentages apply only to boosters having this ratio of transformation. If boosters having a ratio of 2080 to 115–230 are used the amount of boost is increased about 10 per cent. Fig. 76 (*a*) becomes 5.5 per cent, (*b*) 6.05 per cent, (*c*) 11.1 per cent and (*d*) 12.2 per cent. Similarly the chokes in Fig. 77 (*a*) would be 5.5 per cent, (*b*) 5.24 per cent, (*c*) 11 per cent and (*d*) 10 per cent.

Booster Cut-outs. — There are certain precautions which should be observed in the installation of boosters, to protect them from injury. The booster secondary is in series with the line, and current is drawn through its primary windings

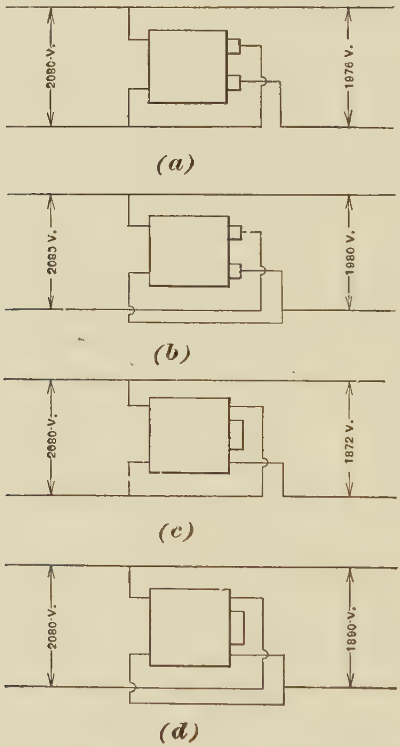


Fig. 77. Connections for Choking Transformers.

in proportion to the load on the line. If the primary of the booster is opened while the secondary is carrying the line current the magnetization of the transformer is greatly increased and the booster acts as a series transformer. This causes a large increase of pressure in the booster, imposing upon its primary coils a high pressure, and the insulation of

a 2200-volt transformer may be subjected to a potential of 10,000 to 20,000 volts or more, depending upon the load carried by the main circuit at the time.

If a fuse is used in the primary the blowing of the fuse creates this condition and the arc holds across the terminals of the block until it burns itself clear and is quite sure to break down the insulation of the primary coil.

The safest method of connecting or disconnecting a booster is to open the main line while putting it in or out of circuit. However, if the service cannot be interrupted, or if it is desired to switch the booster in or out periodically, this may be accomplished by the use of a series cut-out, connected as shown in Fig. 78.

The operation of the cut-out simultaneously opens the primary and short-circuits the secondary of the booster. The

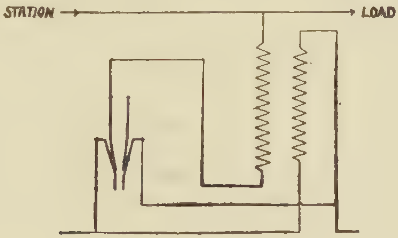
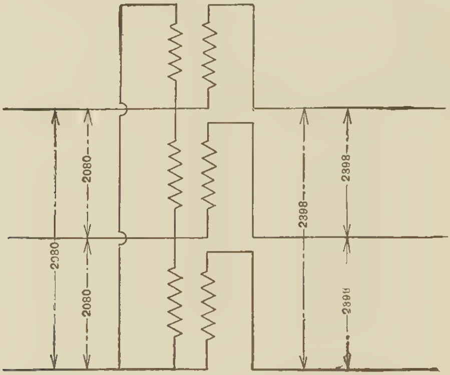


Fig. 78. Booster Cut-out.

switch must be of a type having a positive action, so that arcing will not damage its contacts at the moment the secondary is short-circuited. It must also have sufficient carrying capacity to carry the main line current, and standard series arc cut-outs should not be used where the line current is likely to be over 20 to 25 amperes.

When the augmented booster is used the terminals of the primary winding of the transformer which goes to the cut-out should be connected to that terminal of the cut-out which is shown as not being in use in Fig. 78.

Boosters in Polyphase Systems. — The connections for boosters in a two-phase system are similar to those shown in Fig. 76 for the single-phase system. Where three-wire

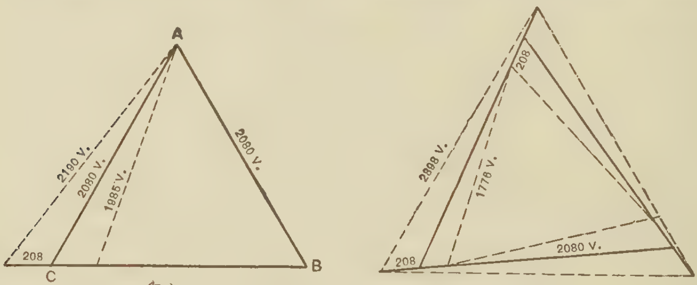


(*a*)

Fig. 79. Three-phase, Three-wire Booster Connections.

two-phase feeders are used the boosters are looped into the outer wires and the pressure is taken from the common wire.

The use of boosters in a delta-connected three-phase system



(*b*) (*c*)

Fig. 80. Effect of Booster in Three-phase Circuit.

is not so simple as is the single-phase application. The booster is looped into the line and pressure is taken for the primary coil from an adjoining phase wire, as in Fig. 79. The insertion of a booster on one phase affects the pressure on two phases,

as shown diagrammatically in Fig. 80, which illustrates the effect of a 10 to 1 booster put into the "C" phase only. When boosting, the pressure from A to C is raised 110 volts, while B to C is raised 208 volts, the pressure coil of the booster being connected from B to C.

The effect of a booster in each phase is seen in Fig. 80 in the larger dotted triangle, and the smallest triangle in the same figure shows the effect of a choke in each phase.

Three boosters are therefore required to keep conditions in balance, in a three-phase three-wire circuit.

The boosting or choking effect when various booster transformer ratios are used in one, two or three phases is expressed in percentages of the primary voltage in the following table:

BOOSTING

Ratios.	10 to 1.			20 to 1.			9 to 1.			18 to 1.		
Booster in	*A B*	*B C*	*C A*	*A B*	*B C*	*C A*	*A B*	*B C*	*C A*	*A B*	*B C*	*C A*
A phase....	10	0	5.3	5	0	2.65	11	0	5.8	5.5	0	2.9
A and B....	15.3	10	5.3	7.65	5	2.65	16.8	5.5	5.8	8.4	2.75	2.9
A, B and C..	15.3	15.3	15.3	7.65	7.65	7.65	16.8	16.8	16.8	8.4	8.4	8.4

CHOKING

A phase....	10	0	4.6	5	0	2.3	11	0	5.06	5.5	0	2.53
A and B....	14.6	10	4.6	7.3	5	2.3	16.06	11	5.06	8.3	5.5	2.53
A, B and C..	14.6	14.6	14.6	7.3	7.3	7.3	16.06	16.06	16.06	8.03	8.03	8.03

In a Y connected four-wire three-phase system the boosters may be connected in such a way that the pressure is controlled in each phase independently of the others. The booster is put in series with the phase wire and the primary is connected from the same phase to the neutral. The connections are the same as for a single-phase circuit if each phase is considered

as a separate circuit, the neutral being regarded as the opposite pole of all phases.

In cases where it may be desirable in an emergency to give 440-volt service by means of 230-volt, 9 to 1 transformers, this may be done by installing a 10 per cent booster in each phase. The secondary connection being made Y for normal operation at 230–400 volts, the pressure is raised to 440 volts by putting the 10 per cent boosters into the primary side of the main transformers. It is, of course, possible to do this in the same way with 10 to 1 transformers, if the system is normally operated at 2300 volts on primary distributing mains.

Booster schemes should, in general, be regarded as tentative remedies, rather than permanent schemes of operation. Their use is unavoidable at times in developing distribution systems in districts where consumers are widely scattered, and this is the field in which they are most frequently employed. They should be eliminated as soon as the density of the load reaches a point which justifies a sufficient number of feeders to make their use no longer necessary.

Auto-Transformers. — The introduction of incandescent lamps of high efficiency having characteristics which render them most durable at the lower voltages has greatly increased the field of application of the auto-transformer. It is desirable in plants using 220-volt and 440-volt systems to have available 110-volt circuits for lighting. Where the proportion of lighting service is small it is sometimes preferable to use a standard transformer as an auto-transformer.

The connections in Fig. 81 are those for two-wire 110-volt distribution on a 220-volt system, the load being assumed at 20 amperes. The distribution of current in the winding is indicated by the figures and arrow heads. It will be seen that the transformer capacity required is equal to the load, when a standard transformer is used.

When the lighting is distributed on the three-wire 110–220-volt system, the transformer carries only the unbalance of current in the two sides of the system, as shown in Fig. 81 (*b*). In this case the unbalance is 5 amperes. The transformer

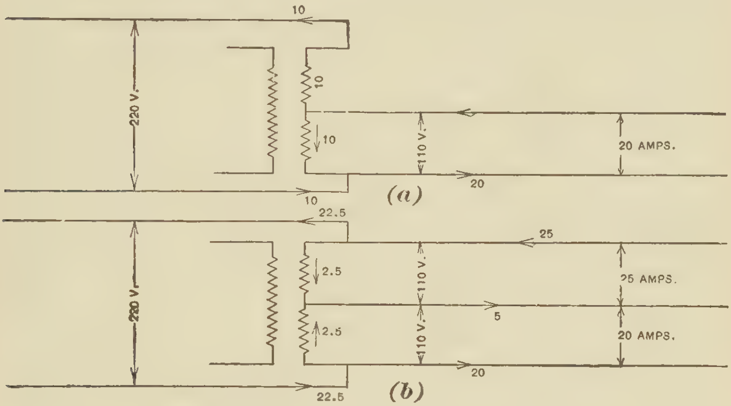


Fig. 81. Auto-transformer Connections.

carries $2\frac{1}{2}$ amperes at 220 volts, and need be only large enough to carry the largest unbalance which is likely to occur. The primary terminals of the transformer are not used in either case and should be well insulated to guard against accident.

In a 440-volt plant, 110-volt lighting may be secured from standard transformers, as in Fig. 82. This requires the use of two transformers in series on the 220-volt side and in parallel on the primary side. It is important that the primaries be in parallel, as the other transformer acts as a choke if the primary terminals are left open, as in the case of a single transformer.

The lighting distribution in a 440-volt system is preferably accomplished by the three-wire 110–220-volt system, as this only requires transformers of capacity equal to the load, while two-wire 110-volt distribution requires that the transformer on the side on which the lights are connected have a capacity

of 1.5 times the load, and the other one must carry half the load, making the total capacity twice the load.

It would be possible, of course, to run a five-wire system or two three-wire systems, and so reduce the transformer

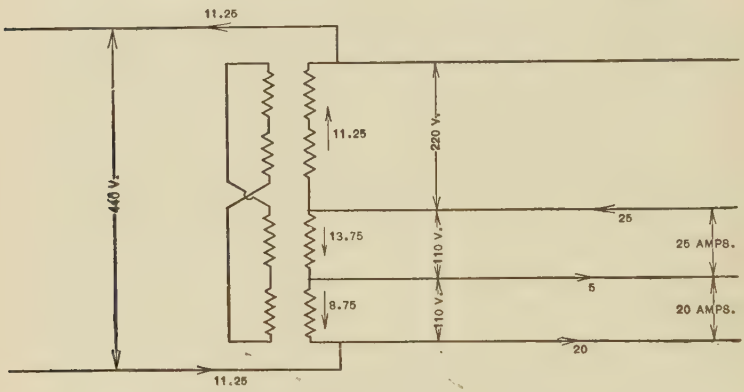


Fig. 82. 110–220 Volts from 440 Volts.

capacity to that of the unbalanced load, but this would not often justify the increased complication of the wiring which would be occasioned by such an arrangement.

Three-phase from Two Transformers. — The cost of transformers for small three-phase power service makes desirable in many cases the use of schemes of connection by which three-phase secondary service may be derived from two transformers. Two schemes of connections are possible for this purpose, one known as the open delta and the other as the T connection.

The open delta connection for a three-wire system is shown in Fig. 83 (*a*). This is merely an ordinary delta connection with one transformer left out. A simple rule by which this connection may be kept in mind is that both primary and secondary are connected in series as if it were a three-wire Edison system. The middle wire of the line goes to the

middle point between the transformer on both primary and secondary.

In order to reverse the rotation the two outside wires must be interchanged on the primary or two of the three crossed on the secondary side.

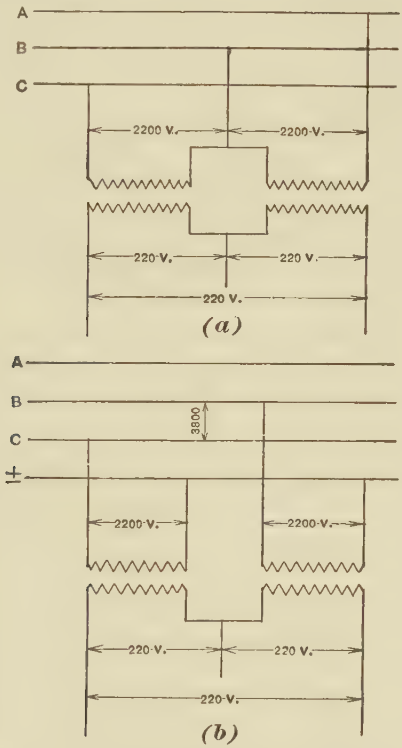


Fig. 83. Open Delta Secondary Connections.

Fig. 83 (*b*) shows the open delta connection supplied from a four-wire three-phase system. In this case the primary is connected to two of the phase wires and the neutral wire. To reverse rotation on the primary side the phase wires should be interchanged.

With the open delta connection the current in the coils is

15.4 per cent more than it is with three transformers. That is, if three 5-kw. transformers are fully loaded by a given installation, they may be replaced by an open delta set of two $7\frac{1}{2}$-kw. transformers, but the coils of the $7\frac{1}{2}$-kw. units will be overloaded 15.4 per cent, at full load of 15 kv-a.

This is evident from an example. Assume that in a three-transformer installation, the current in the secondary line is 17.3 amperes. This places a load on the transformer secondary coils of $\frac{17.3}{1.73} = 10$ amperes. At 200 volts this is 2 kw. per transformer or 6 kw. in all.

If two 3-kw. transformers were used instead of three 2-kw. units, the capacity of the secondary coils would be 15 amperes. But with the open delta connection the current in the secondary coil is the same as the current in the line, and the 15-ampere winding must carry 17.3 amperes or 15.4 per cent overload.

With a three-wire three-phase system, power service may be given by the use of two transformers with the T connection

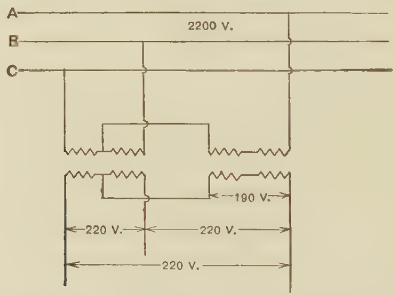


Fig. 84. T Connection, Three-phase.

on both primary and secondary, as shown in Fig. 84. The current overload is 15.4 per cent as with the open delta connection. This scheme cannot be used with standard 2200-volt transformers on a four-wire system as the delta voltage is 3800. It is not possible to use this scheme with two trans-

formers in series as the principle of operation requires that the current passing to the transformer at the left, in Fig. 84, from the other transformer, divide and pass each way from the midpoint. Thus the magnetic field of one part balances the other. When two transformers are used across one phase the magnetic circuits are separate and the balancing reaction cannot take place. The terminal of the middle point of the primary is not brought out in standard distributing transformers and this plan is therefore not often used.

This connection has a slight advantage over the open delta in the three-wire system, as the pressure across the right-hand transformer is but 86.6 per cent of the line voltage, which reduces the iron loss in this transformer about 15 per cent. The inherent regulation is also somewhat better.

Two-phase to Three-phase Transformation. — The T connection may be used in transforming from three-phase to two-phase or *vice versa*, as shown in Fig. 85.

It will be noted that one transformer must have a tap brought out so as to make the ratio of transformation on that unit from 1906 to 220 instead of 2200 to 220 as in the other unit. Standard lighting transformers are not usually equipped with 86.6 per cent taps, but this connection may be quite closely approximated by the arrangement shown in Fig. 85 (*b*), when the transformation is made from two-phase to three-phase. Standard 10 to 1 transformers are used, one phase of the two-phase supply being choked by two transformers, one of which is connected for 9.0 per cent choke and the other for 4.5 per cent.

If the pressure desired for the motor service were 230 volts and the primary pressure were 2080 instead of 2200, the left-hand transformer in Fig. 85 (*b*) should have a 9 to 1 ratio. With a 10 to 1 as the other unit, the 9 per cent choking transformer could be dispensed with.

In transforming from three-phase three-wire to two-phase with standard transformers, the pressure on the right-hand transformer in Fig. 85 (*a*) must be raised by a booster. With a 10 to 1 transformer in the left-hand position, and a 9 to 1

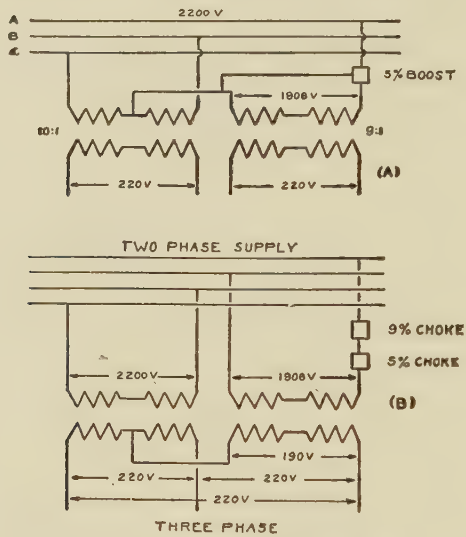


Fig. 85. Two-phase from Three-phase.

at the right, the pressure must be raised 5 per cent by a booster. The primary coil of the booster must be connected from A phase to the center of the T connection, as shown in Fig. 85 (*a*), in order to get the pressure of the booster in phase with the current in the right-hand transformer. If only 10 to 1 transformers are available, the right-hand transformer is boosted 15 per cent instead of 5 per cent. If only 9 to 1 units are to be had, the left-hand transformer is choked 10 per cent and the right-hand unit boosted 5 per cent, to give 220-volt two-phase service.

In deriving two-phase 440-volt supply two sets of transformers may be used, putting them in parallel on the three-phase side and in series on the two-phase side.

It is impossible to derive 440-volt three-phase supply from a two-phase supply except with 440-volt transformers, since transformers will not operate in series on the T-connected side of such a combination.

Two-phase 220-volt service may be secured from a four-wire three-phase system with standard transformers by the use of three transformers connected as in Fig. 86. The unit

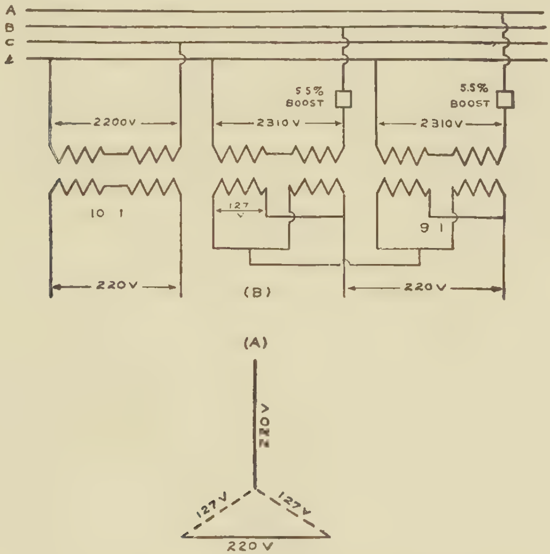


Fig. 86. Two-phase from Four-Wire Three-phase.

at the left is a 10 to 1, connected from one phase to neutral. The others are 9 to 1, connected with their secondary coils in multiple, and are arranged as two limbs of a Y, so that a pressure of 127 volts is required at the transformer terminals to give 220 volts across the outer wires.

The three-phase system is unbalanced by this arrangement, since half the power is taken from one phase and the other half from the other two, making the balance in the propor-

tions of 50, 25 and 25. The capacity of the transformers should be in these proportions.

It is possible to use 10 to 1 transformers for all, but if this is done it is necessary to install 15 per cent boosters in each of the two phases supplying the right-hand transformers in Fig. 86. It is not possible to derive a four-wire three-phase system from a two-phase system with standard transformers.

Single-phase from Three-phase. — In connection with electric welding and work requiring single-phase energy in amounts

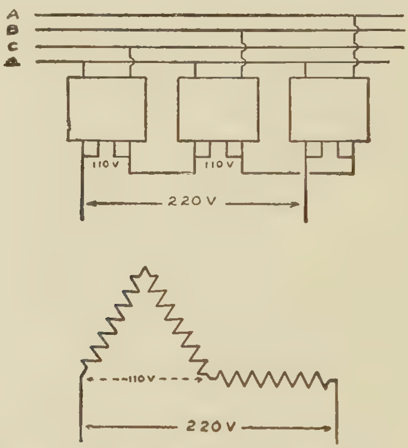


Fig. 87. Single-phase from Three-phase.

so large that the unbalanced load is serious, the load may be distributed between the three phases by a scheme of connections shown in Fig. 87, in which equal currents are drawn from the three phases to supply 220-volt single-phase energy. Each transformer must have capacity to carry half the load, making the total capacity 1.5 times the load.

This plan is not applicable to a delta connected system as all the energy is supplied by one phase with that scheme of connection.

CHAPTER VIII

PROTECTIVE APPARATUS

Historical. — With the introduction of constant potential distribution some form of protection was necessary for generators and circuits which would save them from the effects of an abnormal flow of current when the circuit was accidentally crossed or short-circuited. This problem, which was fairly well solved for the conditions met in the early stages of the art, has reasserted itself with each increase in voltage and in power station capacities. Different solutions have been found for each case and the problem is still a live one.

In the early direct-current plants which were operated at about 110 volts the means selected for the protection of the apparatus consisted of fuses which automatically cut off the supply of electricity when more current was drawn from the circuit than it could safely carry. The presence of an overload or short circuit was thus indicated in a way which required prompt attention. It was found that lead, tin and similar soft metals having a low melting point had a relatively high electrical resistance. This combination of physical properties suggested an automatic cut-out in the form of a fusible connection inserted in the circuit. These early circuits were therefore protected by the insertion of short pieces of soft wire, known as fuses, which were so arranged that the melted pieces could readily be replaced after conditions on the circuit had been restored to normal.

Another and more elaborate method consisted of a solenoid connected in series with the circuit, and provided with a

plunger which tripped a spring and opened the switch in case of overload. This came to be known as a circuit breaker.

The use of fuses for protection against overloads and short circuits in low-tension lighting systems became universal because of their simplicity and low cost. The circuit breaker was used chiefly where the protective device operated frequently.

In its primitive form the fuse consisted of a piece of lead wire secured under binding screws at each end. The uncertainty of this form of contact resulted in fuses blowing when they should not, and tips of copper suitably slotted to fit the binding screws were added. The use of wood blocks was abandoned on account of risk of fire from the arc caused by the melting of the fuse. The use of slate and porcelain, while it eliminated the fire risk incident to the wood block, resulted in the chipping of the surface or the cracking of the block in case of the blowing of the fuse under short circuit with large amounts of power available. The use of porcelain for fuse blocks was prohibited except where the fuse was enclosed, and it was required that where slate or marble was used, a suitable barrier be placed between the terminals, the purpose of this barrier being to hold the heat of the arc away from the surface of the block.

Enclosed Fuses. — The danger of fire from the flash which occurs at the melting of the fuse when mounted on an open block led Edison, at an early date, to devise a form of enclosed fuse which could be easily renewed without the use of tools and which could be refilled when blown at small expense. This is the now familiarly known Edison plug fuse. Originally glass was used as the insulating medium and the cover was made removable, but it is now made of porcelain and the cover is attached so that it cannot be removed without the use of tools. This was found necessary to prevent the covers being left off. This form of fuse is one of the best and least

expensive methods of protecting low-voltage branch circuits carrying loads of 1500 watts and under.

The protection of lines carrying loads larger than 1500 watts is not satisfactory with the plug type of fuse as the explosive force is too great when short circuits occur. The copper-tipped fuse wire known as the link fuse serves this purpose economically, and is quite satisfactory for loads up to 50 kilowatts or more at low potentials. The open link fuse, however, is unsafe unless enclosed in a fireproof box, as the flash caused by the opening of the circuit constitutes a fire risk.

The danger arising from the use of open link fuses has led to the development of a large variety of enclosed cartridge fuses. Most of these consist of a tube of fibrous material in which the fuse is mounted, and a filling around the tube of certain fire-resisting powders which absorb the vaporized metal when the fuse blows and smother the arc. Connection is made at the ends by means of brass or copper terminals, copper being used on the fuses designed for currents of 60 amperes and upwards.

The use of nonporous substances in place of the fibrous tube has not been successful, as the pressure generated by the vaporization of the fuse metal within the tube must have means of escape. The concealment of the fuse wire within the tube makes desirable some device for indicating when the fuse has melted. This takes various forms, most of which employ a hole in the tube which permits a small portion of the arc to burn a paper covering, thus indicating at the surface that the fuse has melted.

The cost of installation and maintenance of cartridge fuses is necessarily several times greater than that of the link fuses. This has greatly retarded their adoption for low potential circuits, where the Edison plug and copper-tipped link fuses are most common. On 250 to 600 volt power circuits the use of cartridge fuses is quite general.

It is too frequently the case that where the designing engineer has provided a safe equipment of fuses of the cartridge type, the operating man permits its safety and effectiveness to be destroyed by the use of temporary devices designed to keep the circuit going but to postpone the expense of renewing the fuse. This condition has been improved somewhat by the introduction of cartridge fuses which can be refused at small expense.

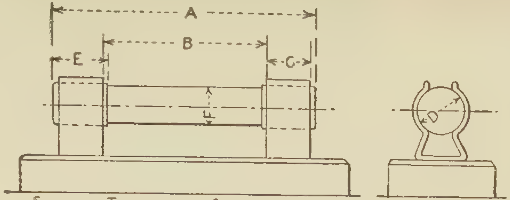
The sizes of cartridge fuses have been standardized by the National Electric Code in order to prevent the use of sizes of fuses which are greatly in excess of the rating of the circuit which they are designed to protect. Thus a fuse which is intended to operate at any current value from 0 to 30 amperes cannot be replaced by an enclosed fuse having a rating of over 30 amperes as the length and diameter of the tube are greater and the fuse larger than 30 amperes does not fit the clips on the 30 ampere block.

The sizes standardized by the National Electric Code are as in the accompanying table.

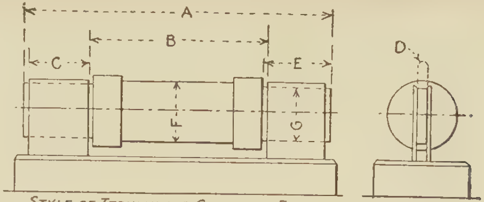
Operation of Fuses. — The operation of the fuse being dependent on the elevation of its temperature, the reliability of its performance on overloads depends upon the rate at which its heat is radiated. This is not so much of a factor in case of short circuit, as the temperature rise is so rapid that radiation has no appreciable effect.

Under normal load conditions the fuse may fail to carry its rated load because of insufficient opportunity for radiation or because of insufficient contact surface at its terminals, which may add to the heat instead of assisting in carrying it away. A fuse with a long length of wire between terminal clips will generally act at a lower current than one made of a short length, and a fuse mounted on lugs of liberal area will carry more than the same fuse connected to small lugs.

TABLE OF DIMENSIONS OF THE NATIONAL ELECTRICAL CODE STANDARD CARTRIDGE ENCLOSED FUSE



STYLE OF TERMINAL FOR CARTRIDGE FUSES
0-60 AMPERES



STYLE OF TERMINAL FOR CARTRIDGE FUSES
61-600 AMPERES

Form 1. Cartridge Fuse — Ferrule Contact. Form 2. Cartridge Fuse — Knife Blade Contact.

Voltage.	Rated capacity, amperes.		A Length over terminals, inches.	B Distance between contact clips, inches.	C Width of contact clips, inches.	D Diameter of ferrules or thickness of terminal blades, inches.	E Min. length of ferrules or of terminal blades outside of tube, inches.	F Diameter of tube, inches.	G Width of terminal blades, inches.		Rated capacity, amperes.
Not over 250	0–30	Form 1	2	1	$\frac{1}{2}$	$\frac{9}{16}$	$\frac{1}{2}$	$\frac{1}{2}$		Form 1	0–30
	31–60		3	$1\frac{3}{4}$	$\frac{5}{8}$	$\frac{13}{16}$	$\frac{5}{8}$	$\frac{3}{4}$			31–60
	61–100	Form 2	$5\frac{7}{8}$	4	$\frac{7}{8}$	$\frac{1}{8}$	1	1	$\frac{3}{4}$	Form 2	61–100
	101–200		$7\frac{1}{8}$	$4\frac{1}{2}$	$1\frac{1}{4}$	$\frac{3}{16}$	$1\frac{3}{8}$	$1\frac{1}{2}$	$1\frac{1}{8}$		101–200
	201–400		$8\frac{5}{8}$	5	$1\frac{3}{4}$	$\frac{1}{4}$	$1\frac{7}{8}$	2	$1\frac{5}{8}$		201–400
	401–600		$10\frac{3}{8}$	6	$2\frac{1}{8}$	$\frac{1}{4}$	$2\frac{1}{4}$	$2\frac{1}{2}$	2		401–600
Not over 600	0–30	Form 1	5	4	$\frac{1}{2}$	$\frac{13}{16}$	$\frac{1}{2}$	$\frac{3}{4}$		Form 1	0–30
	31–60		$5\frac{1}{2}$	$4\frac{1}{4}$	$\frac{5}{8}$	$1\frac{1}{16}$	$\frac{5}{8}$	1			31–60
	61–100	Form 2	$7\frac{7}{8}$	6	$\frac{7}{8}$	$\frac{1}{8}$	1	$1\frac{1}{4}$	$\frac{3}{4}$	Form 2	61–100
	101–200		$9\frac{5}{8}$	7	$1\frac{1}{4}$	$\frac{3}{16}$	$1\frac{3}{8}$	$1\frac{3}{4}$	$1\frac{1}{8}$		101–200
	201–400		$11\frac{5}{8}$	8	$1\frac{3}{4}$	$\frac{1}{4}$	$1\frac{7}{8}$	$2\frac{1}{2}$	$1\frac{5}{8}$		201–400
	401–600		$13\frac{3}{8}$	9	$2\frac{1}{4}$	$\frac{1}{4}$	$2\frac{1}{4}$	3	2		401–600

The action of enclosed fuses is in general somewhat more accurate than that of open link fuses on account of the more restricted radiation of the enclosed fuse.

The time required to cause a 5-ampere fuse to operate at different loads is illustrated in the curve of Fig. 88. This

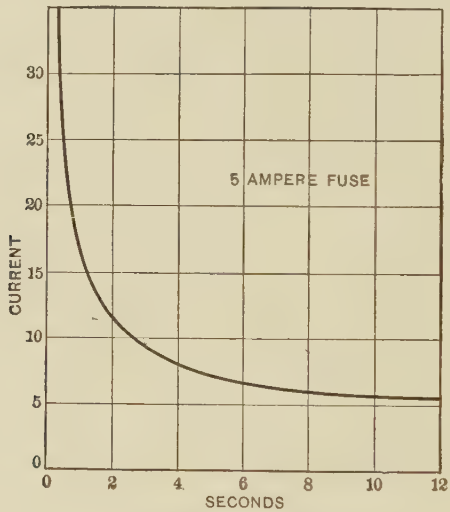


Fig. 88. Time Element of Fuse.

curve is typical of the action of fuses of all sizes, the absolute values varying with different types and capacities.

The law governing the operation of fuses was worked out by Preece in 1888. It may be stated with sufficient accuracy for general purposes in the form, Current $= a\sqrt{d^3}$, d being the diameter of the wire expressed in inches. The value of the constant a is different for each metal. For copper it is 10,244, for aluminum 7585, for lead 1379, for tin 1842 and for iron 3148.

For instance with a No. 10 B. & S. copper wire having a diameter of .102 inch, the fusing current is

$$C = 10{,}244 \times \sqrt{(.102)^3} = 334 \text{ amperes.}$$

The fusing currents for some of the smaller sizes of copper and aluminum wire are as follows:

Size Wire.	8	10	12	14	16	18	20	22	24	26
$\sqrt{(d)^3}$	.046	.0325	.229	.0162	.0114	.0081	.0057	.004	.0028	.002
Fusing current copper	472	334	235	166	117	83	58	41	29	20
Fusing current aluminum	349	246	174	123	86	61	43	30	21	15

Use of Fuses. — On low potential circuits the use of fuses inside of buildings is prescribed in detail by the National Electrical Code. The rules of the Code are based upon the general principle that each sub-division of load down to 660 watts must be protected by a fuse of such size as to operate at about the rated capacity of the circuit. Also that each group of circuits must be provided with a fuse at every point where there is a change to a smaller size of conductor. It is the purpose of the Code rules to have the fuse blow which is next in order from the source of supply. Thus, on the smaller circuits, the occurrence of a short circuit blows a small fuse and keeps the resulting arc down to the minimum size. The fire risk is thus kept at a minimum.

With outside distribution circuits, it is not necessary to provide so complete a system of fusing as that prescribed by the Code for inside work, since the fire risk is much less. Furthermore, the deterioration of fuses when placed out of doors, is apt to be such that they blow when no emergency exists, and service is unnecessarily interrupted.

Hence it is usually desirable to use as few fuses as possible with outside distributing lines. The number should not be reduced too greatly however, since the amount of service interrupted becomes excessive.

Alternating Current Primary Mains. — The standard system of distributing 2200 volt alternating current energy, by branches which are not inter-connected with other sources of supply makes the problem of placing fuses on such systems a difficult one. The practice is not fully standardized because of differences in local conditions and in the size of the system.

In smaller systems where the emergency man is close at hand and the conditions most likely to cause trouble are better known, it is usual to find more fuses used, than in a system embodying a larger number of circuits, and greater distances. In the larger systems where plenty of power is available to sustain a short circuit for a few seconds without danger to sub-station apparatus, it is usually considered preferable to depend largely upon the feeder circuit breaker at the substation.

Many cases of short circuit on overhead lines are temporary and clear themselves as soon as the circuit breaker opens. When this class of trouble occurs, the load of the feeder is interrupted for only a minute or two, whereas, if fuses are used, the load of the branch controlled by the fuse is interrupted for perhaps an hour or more until the emergency man can learn of the trouble and replace the fuse.

During severe lightning storms, fuses are especially likely to be blown by the discharge of arresters or by momentary discharge at other points. The replacement of fuses following a storm requires considerable time in a large system, and it is usually considered preferable to omit practically all primary main fuses, depending upon the station circuit breakers.

Fuses are sometimes used in cases where trees or other conditions are a frequent cause of interruptions on the smaller branches.

With the discontinuance of the use of fuses, it is necessary to provide a suitable disconnecting device, which can be used

as a means of isolating sections of the circuit in emergencies so that service may be restored on the remainder of the feeder By this means the branch on which there is trouble may be located quickly if the principal mains are arranged so that they may be opened separately.

In the case illustrated in Fig. 89 the mains are radiated from a center of distribution at which the feeder may be

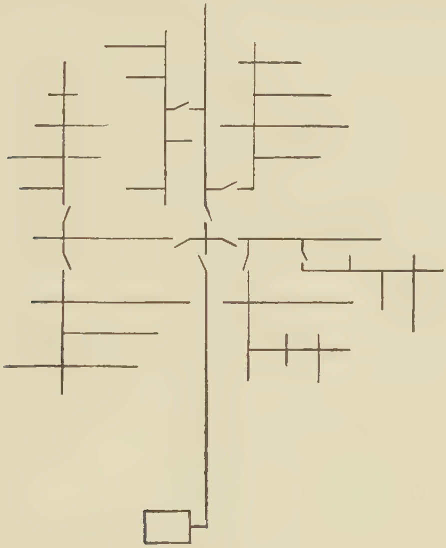


Fig. 89. Use of Disconnectives.

quickly cut up into four parts, each of which may be disconnected successively until the one which is short-circuited is located. Having determined which branch is in trouble, the emergency man may proceed to follow the route taken until he reaches the next junction point. Here similar tests are made to find out which sub-main is responsible for the interruption and so on until the trouble is located. These disconnectives may be single conductor disconnecting pot-heads or knife switches on small branches.

Low-Tension Networks. — In overhead low-tension networks, using weatherproof insulated wire, the danger of short circuit is very slight if the lines are properly maintained, and it is therefore usual to omit fuses except at important points of supply. Fuses, if put at each junction, are likely to be a source of trouble by blowing when they should not rather than a protection to the line against interruption. The work of repair is relatively quick, and it is therefore justifiable to risk larger areas than with low-tension underground lines.

In direct-current underground low-tension networks sectionalizing must be done with great thoroughness, owing to the density of the load, the length of time required to make repairs and the importance of the service.

Trouble on a distributing main or service taken from it must be limited to the block in which it occurs, and if lines are carried on both sides of the street it must be restricted to one side of the street. Trouble on an underground main is usually of such a nature that considerable time is required to make repairs. For this reason it is usual to place fuses at all junction points, so that in case of trouble the section affected will cut itself out at each end.

In the early Edison systems junction boxes were equipped with copper-tipped fuses made of sheet metal of lead and tin, which produced a large amount of vapor when they blew under short circuit and were subject to a tendency to depreciation, which caused them to heat and blow unnecessarily at times. This difficulty was obviated later by the introduction of sheet-copper fuses, such as those shown in Fig. 90 which are now in general use. This greatly reduced the weight of metal required and therefore the severity of the arc at the time of the blowing of a fuse. The section of the copper at the point where fusion takes place is designed to carry its normal rated load without undue temperature rise

and to fuse at about twice its normal rating. Two types of junction boxes which are used in connection with modern cable systems are shown in Figs. 90 and 91. The one shown in Fig. 90 is installed on the wall of the manhole, while the other appears on the surface of the street.

The feeders in a low-tension network are fused at the point where they connect into the main system, to protect

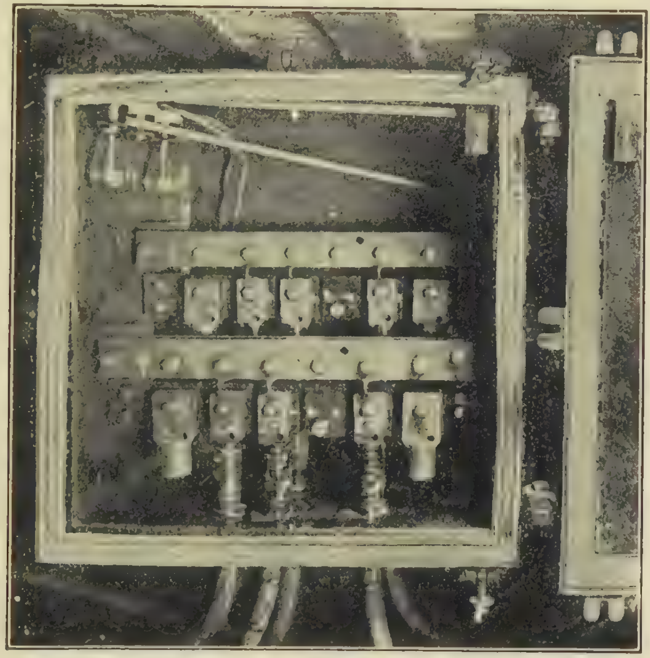


Fig. 90. Cable Junction Box, Manhole Type.

the network against trouble on the feeder. It is not usual in large systems to provide fuses on these feeders at the station since the operator on duty can open the switch and disconnect the feeder in case it is necessary. The likelihood of feeder fuses going out under emergency conditions when they should not, makes it preferable to omit protective devices at the

switchboard, and depend on the operator to disconnect in case of trouble on a feeder. Such trouble is very rare in cable systems and increased reliability is secured by this

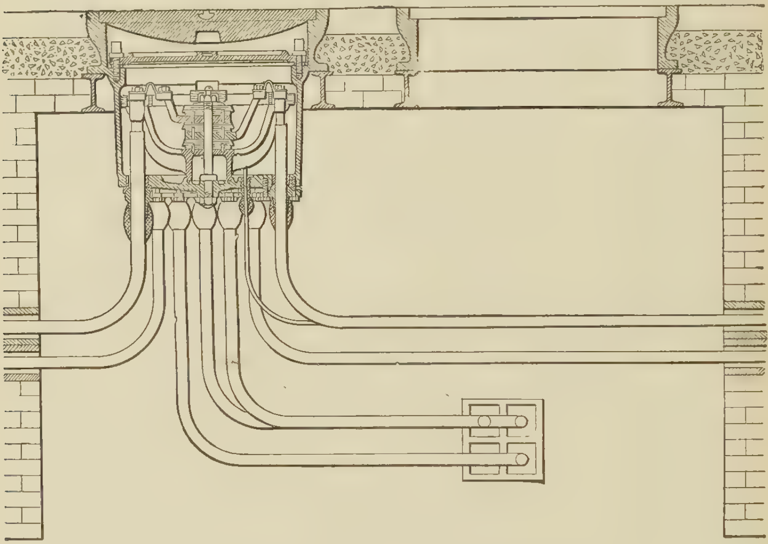


Fig. 91. Surface Type Junction Box.

practice. In some cases reverse-current circuit breakers are placed at feeder ends.

Alternating-current Networks. — The smaller interconnected secondary main systems are frequently arranged along a single street in such a way as not to make a gridiron of mains, but only a succession of mains touching end to end. In such cases fuses are useful as a means of isolation in case one section only is interrupted at time of heavy load. Sectionalizing fuses of this kind are placed midway between transformers.

Where the network is so complete as to form a gridiron the fuse protection is similar to that used in direct current net-

works. There are, however, additional protective methods required in connection with the transformers and primary distribution system in order to secure the high degree of reliability required in a central business district.

These are fully discussed under the heading of Networks in Chapter VI, on Secondary Distribution.

Transformer Fuses. — Line transformers should be provided with primary fuses of such size that they will not blow unnecessarily, and it is not advisable to attempt to protect transformers against ordinary overloads on this account. It is therefore usual to provide primary fuses having about twice the normal rated capacity of the transformer. The following table represents common practice on 2200-volt systems:

Kw. capacity.	Size fuse.	Kw. capacity.	Size fuse.
	Amperes.		Amperes.
1	10	15	15
2	10	20	15
3	10	25	25
4	10	30	25
5	10	40	50
7½	10	50	50
10	10	....	....

The porcelain type of fuse furnished with the transformer which has proven very satisfactory for transformers up to 20 kw. is illustrated in Fig. 92. The removable porcelain plug carries contacts on which the fuse is mounted, and the heat formed by the melting of the arc produces an explosive action which blows out the arc. This form of fuse is very satisfactory up to 15 or 20 amperes at 2200 volts.

For capacities above 25 amperes, there are various types of fuses in use. The cartridge fuse is effective when kept dry, but when placed in a housing out of doors, it is difficult

to prevent the filler from absorbing moisture and thus losing its arc smothering characteristics to a large degree.

The amount of energy dissipated in the arc when the fuse blows under short circuit is so great that it is a very difficult

Fig. 92. Transformer Fuse Block.

matter to design a fuse block which will not be seriously damaged, if not destroyed by the action of the arc.

Aluminum is used as the fuse metal very generally because of its low melting point and high conductivity, a combination which produces less vapor than lead wire. It is, however, subject to oxidation and crystallization which renders it somewhat troublesome in the capacities under 50 amperes.

Various forms of fuses other than the cartridge type have been devised from time to time for use on primary lines and larger sizes of transformers. Most of these depend upon the explosive action of the arc to blow itself out.

Other forms of fuse depend upon the action of a spring which separates the terminals widely when the fuse melts.

In one fuse of this type (Fig. 94) the fuse is enclosed in a glass tube which is filled with carbon tetrachloride which promptly quenches the arc.

Several types of fuse are available in which the fuse link is partially immersed in oil. When the fuse is vaporized in the air above, the oil extinguishes the arc and protects the contacts from burning. This type is shown in Fig. 93.

Circuit Breakers. — Under circumstances where automatic cut-outs operate at frequent intervals on circuits operating at high voltages or controlling loads of 100 kw. and upwards, the circuit breaker is the preferable means of protection.

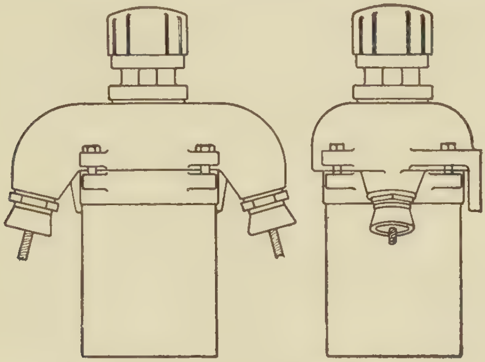


Fig. 93. Oil Type, Primary Fuse.

In general the circuit breaker is expensive in first cost but inexpensive in operation, while the use of fuses involves a considerable maintenance charge but with a small first cost.

In mixed electric lighting and power systems the load is usually steady, and protective devices are not called upon to act except in case of line trouble. The use of fuses is therefore generally preferable in such systems except on feeder and transmission lines which carry large loads at high voltages where the use of fuses is not feasible.

On low-potential circuits the circuit breaker consists of a switch of suitable design, with which is combined a coil connected in series with the circuit so arranged that it will lift a movable core and release a spring-actuated mechanism which opens the switch. This plunger is designed to operate whenever the current exceeds a predetermined value.

Circuit breakers are commonly designed so that they may be adjusted to operate at any point between 80 and 150 per

cent of their rated capacity. It has been found in practice that a magnetizing force of about 1000 ampere turns is ample for the operation of the tripping device.

In high potential systems the design of the circuit breaker is modified somewhat by the fact that a series transformer may be installed at a convenient point in the main circuit and

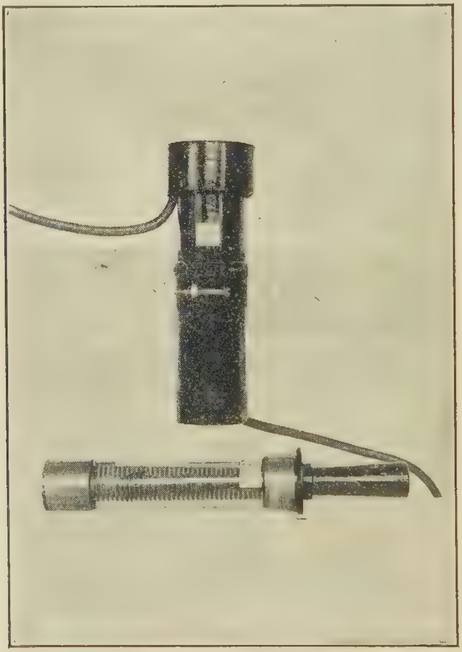


Fig. 94. Carbon Tetrachloride Fuse.

small wires carrying a few amperes may be led from the series transformer to operate the tripping coil of the circuit breaker.

On circuits operating at pressures above 600 volts the switch is commonly of a design which breaks in oil. The use of the series transformer on such circuits serves the double purpose of providing a small current for operating the tripping device and of insulating the mechanism from the high-potential circuits.

Circuit-Breaker Control. — The operating mechanism of the circuit breaker is controlled by hand or electrically by solenoids.

In hand-operated breakers the energy required to open the circuit is usually stored in springs during the act of closing. The overload or reverse-current trip releases the spring mechanism which in turn opens the breaker.

In electrical operation the power for both closing and opening the circuit is supplied through solenoids or motors. The larger sizes and higher voltage breakers are usually controlled electrically on account of the power required and because of the greater facility of operation permissible with remote controlled switches. The latter feature is quite essential in large systems where the number of switches to be handled during an emergency demands a system of control by which an operator may work rapidly and without great effort.

Since direct current is usually available in stations and substations from the exciter system, and is often safeguarded by a storage battery, it is usual to use direct current for the operation of solenoid controlled breakers, where possible.

Circuit breakers which are operated by motors may be controlled from an alternating current supply. Circuit breakers are designed to open all poles of the line simultaneously in three-phase three-wire systems. In two-phase systems and in the four-wire three-phase system, single-pole or two-pole breakers are often used.

Relays. — With electrically controlled circuit breakers the protective device is really the relay which energizes the control circuit. This consists of an alternating-current solenoid energized by a current transformer and having a plunger which closes the direct-current circuit and thus energizes the mechanism of the circuit breaker as shown in Fig. 95.

Relays may be classified in accordance with the principle upon which they operate, and with the time element which they embody, as follows:

Overload or over-current relays.
Power or reverse power relays.
Differential relays.
Inverse time relays.
Definite time relays.
Instantaneous relays.

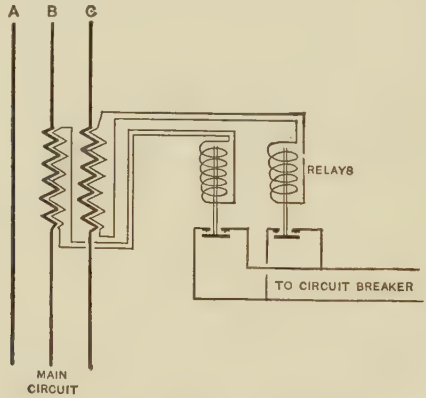


Fig. 95. Relay Connections.

Other special designations are sometimes used for relays for specific purposes, as for voltage or frequency variations.

Overload or over-current relays operate when the amperes have exceeded the predetermined value for which they are adjusted.

Power relays are actuated by a wattmeter mechanism and operate above or below the desired value as the case may be. Reverse power relays operate only when the direction of flow of power is reversed. Power relays operating in one direction only are known as directional relays.

Differential relays are arranged to be normally in balance but to operate when the balance is destroyed. Such relays may depend upon a balance of currents or a balance of voltages.

Inverse time control may be applied to the operation of any power or current or voltage relay. The effect of such control is to cause the relay to complete its travel after a time interval which is increasingly shorter as the current strength or power flow is greater. Thus a relay which is set to operate in 2 seconds at 150 per cent load may operate in 1 second at 300 per cent load or in .2 second at 1000 per cent load. This is accomplished by suitable damping devices on the relay.

A definite time adjustment of a relay is one which allows the relay to complete its travel only after a predetermined interval, such as 1 second or 1.5 seconds. Instantaneous adjustment is one which is not damped in any way and the travel is completed in a fraction of a second by any volume of current sufficient to cause its operation.

In the control of automatic substations certain types of relays are used which require two or more impulses before acting. Such relays are sometimes known as notching relays.

The arrangements of relays on a feeder or transmission line must be such that the occurrence of a short-circuit between any two wires will operate the breaker. On single-phase circuits one relay is sufficient to accomplish this. On two-phase three-wire systems carrying lighting and power it is desirable to provide separate relays and circuit breakers for the two outer wires so that only one phase is interrupted in case of trouble, which does not short-circuit both phases. This is also true of the four-wire two-phase system. In the three-phase three-wire system the occurrence of a short-circuit between any two wires interrupts service on all phases, and relays are required in two wires so that at least one will open the circuit in case of trouble on either phase. The circuit breaker is therefore a three-pole breaker.

In the four-wire three-phase system or in a three-wire three-phase system having the neutral point of the generator winding grounded, it is essential that relays be installed in each phase wire since the occurrence of a ground on either phase conductor results in a short-circuit. In the four-wire system only the relays on the phases affected come into action. In case of a ground on one phase the circuit breaker on that phase opens without interrupting lighting service on the other two phases.

Application of Relays. — The overload relay is used in general on lines which are not interconnected with others and where the only duty required of the relay is that it cut off the supply in case of short-circuit.

Such relays are usually given an inverse time adjustment, so that they will not operate readily on momentary overloads or grounds, but will open the circuit quickly in case of a short-circuit. This is the normal situation with distributing feeders.

In the case of a line which supplies a substation in conjunction with other lines, the lines are connected to a source of energy at each end and must be provided with relays at the substation, as well as at the power station. This situation is commonly met by the use of overload relays at the supply end and reverse power relays at the substation end. A failure on one line is, thus, isolated by the opening of circuit breakers at each end.

Where a line supplies two or more substations or industrial customers arranged tandem, it is desirable that a failure shall not interrupt any substation except those beyond the section where the failure has occurred. This is accomplished by the use of definite time relays so adjusted that the breakers farthest from the point of supply will open in the shortest interval and those at the supply station shall take the longest

time. It is usually considered that the largest setting should not exceed 2.5 seconds, and the others are spaced about .5 second apart. The application of this principle to a ring circuit having five substations is shown in Fig. 96. The various sections of a ring are provided with relays which are uni-directional, that is, will operate only on energy passing in one direction through them. By placing such relays in each section of the line and connecting them to operate in opposite directions a fault in the cable of any section will cause the

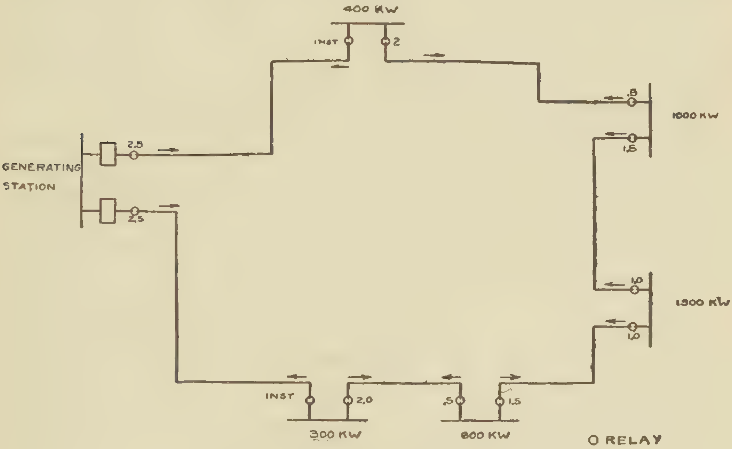


Fig. 96. Reverse Energy Relay.

two relays for that section to operate the circuit breakers and cut the section out. However, in this scheme, the energy passing to the fault must pass through adjoining sections as well, and may cause one end of those sections to open unless the relays are provided with definite time limit adjustments, which are so set that the sections farthest from the source of supply will operate first. This means that the time setting of relays must be highest at the station end and be gradually reduced as each successive relay is passed, until, at the far end of the ring, the setting is practically instantaneous.

These settings are indicated in seconds in Fig. 96 for each relay. It is apparent that this scheme is not adaptable to an extensive network but applies to ring systems having not over 5 or 6 substations or wholesale consumers. If the number of stations supplied is larger than this, the time setting of relays at the supply point may be so great that in case of a fault in the section of cable nearest the point of supply, the time required to open the breaker may be sufficient to cause serious injury to the supply station apparatus.

Reverse power relays depend upon a wattmeter action for their operation and, thus, require both potential and current transformers. The added space and expense for such relays thus tends to restrict their use to a minimum.

The operation of relays on lines operating in parallel is sometimes unsatisfactory, because of the fact that so much current is drawn into the short-circuit that relays are operated at other points of supply than those immediately adjacent to the point of failure, thus unnecessarily interrupting service on lines which are not defective.

Difficulties of this kind increase with the size of the system and the complication of connections.

Differential systems of relay operation were devised to avoid these troubles and were early applied in a large way to a general transmission network by Merz and Price, at Newcastle, England. They are applied to the protection of cables, transformers, and, in some cases, to generator windings.

As applied to a cable, the differential system is based on the principle that the current flowing in a section of line between two terminals is the same at each end, except when a fault occurs.

By providing current transformers at each end of the section and connecting their secondaries together through a pilot cable, paralleling the main cable, the effect of the current passing in at one end is balanced against that of the cur-

rent leaving the section at the other end, and no action results at any value of current while this balance exists. When a short-circuit occurs in any section of cable, current flows from each end of that section to the fault, and the effect on the relays is additive, producing prompt action of the relays and cutting off the supply at each end of the cable.

The connections for one phase of a three-phase line so protected appear in Fig. 97.

In Fig. 97 it will be seen that there is a series transformer in each conductor at each end. The secondaries of these cur-

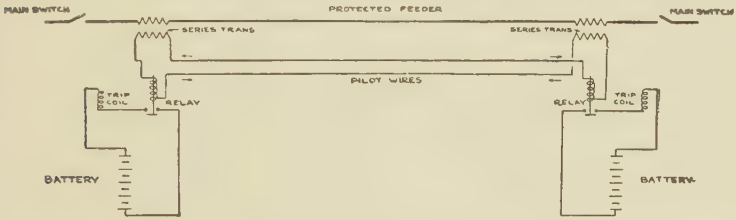


Fig. 97. Merz-Price Relay.

rent transformers are connected in opposition to each other through pilot wires. There is an ordinary relay at each end by which the switch controlling the section of line is actuated.

The flow of current passing through adjoining sections of the line to the faulty section has no effect on the balanced relays of those sections, and no false operation of relays is likely to occur from that cause.

At higher voltages, the charging current of the cable insulation sometimes makes necessary some adjustment of the current transformer ratios to get a true balance.

Differential relays may be applied to the protection of two or three parallel circuits if of so nearly equal length and size as to divide their loads properly by the method shown in Fig. 98. In this scheme the current from two phases is combined magnetically by two relay coils acting on one plunger in opposition to each other. In case of a failure on Line 1,

the excess current drawn by the short-circuit destroys the balance and operates the plunger in the relays, 1–3 and 1–2. The trip-coil of the circuit breaker on Line 1 is in series with these two relays and is operated when both close at the same time. A similar arrangement exists in the case of the other two lines.

This arrangement is successful for a few lines, but becomes very complicated as the number of lines is increased.

In the plan shown in Fig. 99, the balance is effected between the opposing voltages of the secondary coils of the cur-

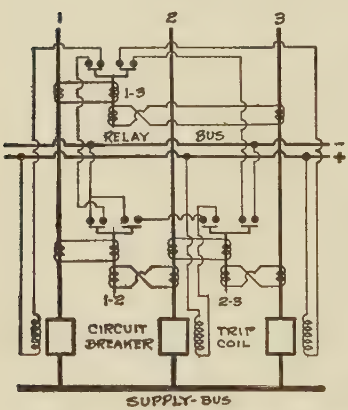


Fig. 98. Parallel Feeder Protection.

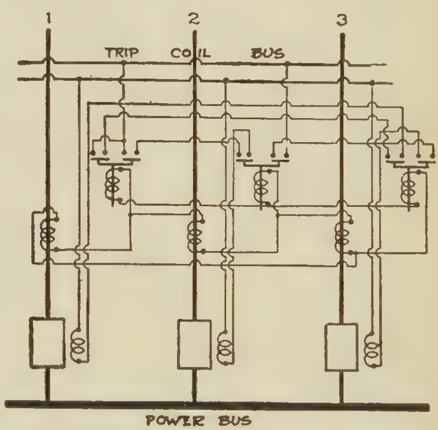


Fig. 99. Voltage Balanced Relays.

rent transformers, and this is termed "electrical," or "voltage balancing."

In the scheme of protection for parallel lines, shown in Fig. 98, the balance is effected through magnetic cores. This plan is also employed for the protection of substation transformers, the currents entering and leaving the apparatus being balanced against each other.

With voltage balancing the current transformers must be provided with specially designed cores to permit operation without the current flow which is normal in series transformers.

The most effective field for the differential relay is in situations where there are numerous substations with interconnecting lines between forming a network.

The application of this system to a network of lines and a group of substations is shown in Fig. 100. This group includes a number of industrial substations having loads of 300 to 1000 kw. and others serving general distributing systems

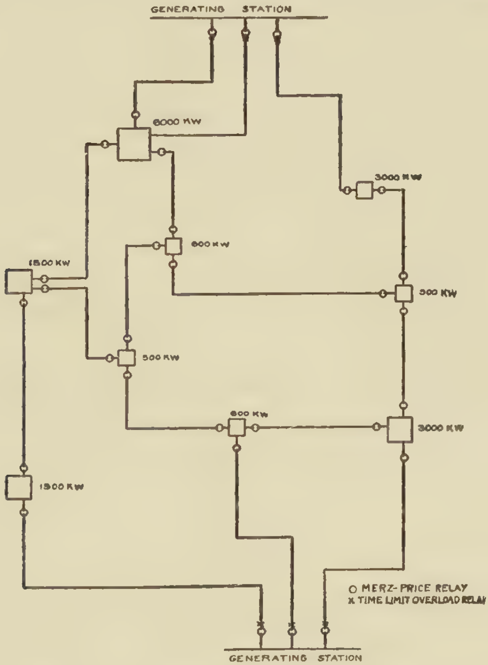


Fig. 100. Protected Transmission Network.

aggregating larger amounts. The advantage of parallel operation is usually greatest with smaller substations as the larger substations have loads which more nearly fit the capacity of the lines supplying them.

The application of differential relay schemes to the protection of cables is restricted by the cost of the pilot cable

installation, which is usually in excess of the cost of relay installations which can be made within a substation. In the average case, the pilot cable adds about ten per cent to the cable investment.

For overhead transmission, the pilot cable must be carried on separate supports, and the percentage of added cost is higher than for underground cables.

Hochstadter has avoided the use of separate pilot wires in the system in Cologne, where the cable is made with copper ribbon worked into the insulation in such a way as to be well separated from the conductors carrying the main power supply. These ribbons serve as the pilot wires, thus avoiding the necessity for a separate duct system or separate lead sheath.

A still further simplification has been effected in a scheme using split conductor cable, as shown in Fig. 101. Each

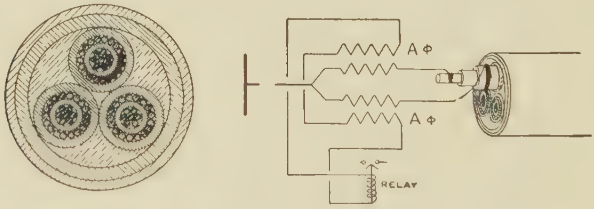


Fig. 101.

polarity of a three-phase cable is divided into two equal parts which are insulated from each other, making it virtually a six-conductor cable. The current divides equally between the two parts of a conductor under normal conditions. In case of a fault in the cable, it is quite probable that one part of the conductor will draw more current than the other, as the parts are separately insulated. The balance between the two current transformers at the terminal points which are opposed to each other is destroyed and the relays operate to open the circuit breakers at each end, cutting out the faulty cable.

The principal objection to this plan is the complication introduced in cable jointing operations by the splitting of conductors.

Reactors. — Reactance coils, having non-magnetic cores, are sometimes used as a means of protecting station apparatus from the effects of short-circuits occurring in or near the station where there is a low reactance in the circuits and equipment and the current drawn through the short circuit would, therefore, be very large if reactors were not used.

Such reactors are mounted on frames of non-flammable material at a convenient point near the supply bus. In large power stations they are used to limit the energy flowing from generators and as a sectionalizing connection between different parts of the bus. They are also used to limit current flow in transmission cables in case of short circuit or ground in the cable.

In substations they are useful as a protection to the general service when placed on outgoing feeders supplied at the transmission voltage, and in large substations may be justified as a protection to distribution feeders at 4000 volts. In the average substation the transformer reactance is sufficient to limit short-circuit current on 4000-volt feeders to a safe value, as the reactance is from 6 to 8 per cent at rated load.

Reactors in feeders or transmission lines are provided with about 5 per cent reactance and the short-circuit current flow is restricted to from 15 to 25 times full load current by the combined effect of reactors, lines, transformers, and generators.

The use of reactors on distributing feeders in series with the reactance of lines and transformers through which they are supplied is likely to result in an excessive range of pressure variation, and this is the principal limitation of their use.

The effect of reactance of various amounts on the regulation

of loads of different power factors is shown in Fig. 102. It will be noted that regulation is poorer at the power factors commonly found in industrial power installations than it is with lighting installations where power factors above 90 are usually found.

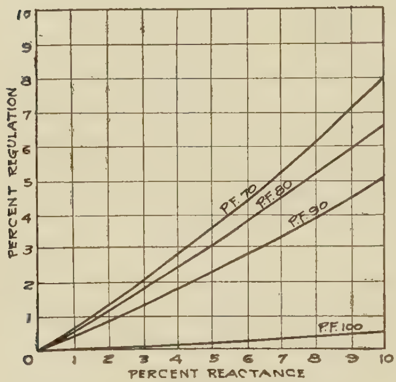


Fig. 102. Voltage Drop in Reactor.

However, it is fortunate that the per cent regulation is less than the per cent reactance as this gives protection which is greater proportionately than the increase in voltage drop.

Protection from Lightning. — Overhead lines are subject to the influence of static electricity in the atmosphere, and in parts of the country where lightning storms are common during the summer months, the problem of protection of service and equipment is often a difficult one.

Electrostatic charges accumulate on the open conductors of a circuit, at times when charged clouds are passing above the line, or by the gradual transfer from drops of rain, fog or snow as they touch the wires.

The sudden release of a charge which accompanies a lightning stroke from cloud to cloud or to earth, liberates the induced charge on the line and causes an abrupt rise of potential which must find a path to earth. It is this sudden release which is most likely to puncture insulation and injure apparatus. This discharge is in the nature of an impulse which is very severe in the immediate vicinity of the lightning flash and rapidly diminishes in force as the wave travels along the line. In lines carried on wooden poles, the discharge may go to

ground over the insulators and splinter one or two poles without being felt seriously by equipment only a few hundred feet distant.

The function of a lightning arrester is to provide a point at which the static charge or the impulse induced by a lightning stroke may pass to earth without injury to line insulators, transformers and other equipment.

The arrester must further be so designed that though it will permit the high potential charge to be relieved, it will not permit the working potential of the line to maintain an arc when it is established.

This result is accomplished with reasonably good success in several types of lightning arresters which are described in a following paragraph.

In primary or transmission systems not having a grounded neutral point, the problem of stopping the flow of power after the lightning discharge has passed is somewhat easier of solution than with a grounded neutral, as the power current must pass through two arresters in series. With a grounded neutral, every discharge to ground is followed up by line potential which requires a higher resistance and more gaps in series to hold the power current in check. However, the arrester on the neutral conductor in such systems may be a 300-volt arrester of simple design.

Types of Arresters. — The natural method of establishing a path which will have a high resistance to the flow of the line current is to arrange a suitable number of air gaps. The early 1100-volt single-phase systems were protected very satisfactorily by arresters of this type. These arresters failed, however, when used at 2200 volts with ample power at the source and it was necessary to add a graphite resistance rod in series with the gaps.

The simplest form of arrester is an air gap which will

permit an accumulated or released charge to be discharged to earth.

At voltages below 300 this can be done without the power current following and no current limiting resistance is needed. Such arresters are used on extended secondary systems and on the neutral conductors of primary distributing systems.

At 2300 volts to ground it is necessary that a current limiting resistance or equivalent means be employed, to prevent an arc to ground following the arrester discharge.

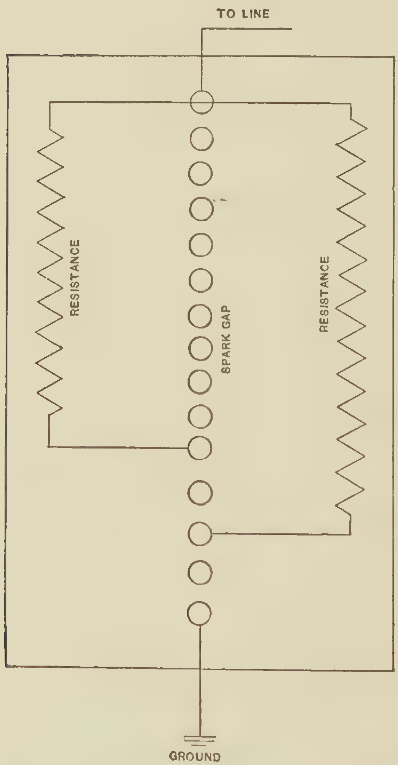


Fig. 103. Multi-path Lightning Arrester.

In one type the resistance takes the form of a rod of a graphite composition in series with a number of gaps which varies with the line voltage. At 2300 volts 4 to 6 gaps are used. The resistance rod and gaps are enclosed in a porcelain tube making a weather-proof device requiring little maintenance expense.

Other forms of arrester with spark gap and resistance have the discharge gaps arranged in parallel paths so adjusted as to make the arrester pass discharges of a wide range of frequencies.

In this arrester the proportions of the parts are so designed that the high frequency lightning discharges pass across the sparking cylinder gaps to

earth, while potential surges at lower frequencies follow the paths through the resistance rods. It thus takes care of high potential disturbances of all kinds whether they originate from atmospheric electricity or from surges of energy within the system.

This type of arrester, Fig. 103, is also used for transmission lines up to about 10,000 volts. Its wide range is more valuable in this field than in 2300-volt distribution.

A specialized form of the spark gap arrester is shown in Fig. 104. This is known as the compression chamber arrester and consists of a series of spark gaps arranged inside a porcelain tube, in series with a resistance rod which occupies the upper part of the tube. The gaps are made more susceptible to discharge by grounded pieces of iron in "U" shape, called antennæ, which are placed across the bottom of the tube and extend several inches up the sides. These serve to modify the potential gradient of the gaps so that about twice as many gaps can be used in series with the resistance as it is possible to use without the antennæ. This enables the 2300-volt arrester of this type to extinguish the arc with a resistance of about 25 ohms.

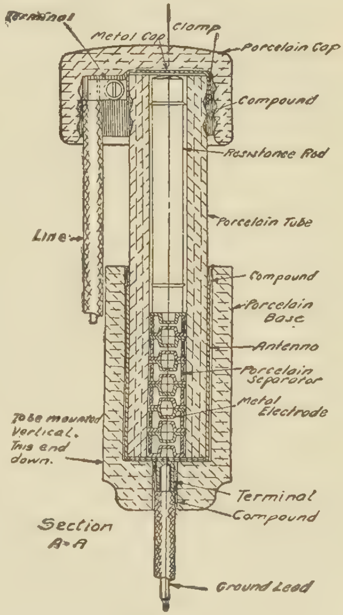


Fig. 104.

The top of the tube is sealed so that the heat of a discharge produces a pressure inside the porcelain, and this in turn assists in putting out the arc.

The line terminal is brought out at the top and the ground terminal at the lower end of the tube.

The electrolytic type of aluminum cell arrester is based upon the fact that aluminum when placed in a suitable electrolyte is quickly coated with an insulating film of oxide when current is passed through it. This almost entirely stops the flow of electricity until the pressure is raised above the critical value of about 350 volts per cell.

A discharge of lightning may thus pass through an arrester made up of a number of cells in series, but as soon as it has passed the line, current cannot follow since the film at once shuts off the flow of current.

The operation of this arrester requires that it be charged by connecting it to the line once a day to keep the film in operative condition, which in practice is objectionable in many cases.

A modified form was, therefore, developed, in which the oxide film principle is used, but the liquid electrolyte is replaced by a pasty medium of such a character that the film is not dissolved and the arresters may, therefore, be installed without provision for daily charging. In the usual form this arrester consists of a stack of disk shaped sections, the number of disks varying with the voltage of the line.

A spark gap is put in series with the arrester to isolate it from direct connection with the line and the length of this gap is also adjusted according to the voltage of the circuit.

This arrester is provided with weather shields as shown in Fig. 105. This is a high voltage unit for transmission line work.

In a smaller form this principle is applied to a 2300-volt arrester of the porcelain tube type. The pasty medium is made in the form of pellets which fill a portion of the tube in series with the air gap and serve to limit the line current in lieu of a resistance rod. This arrester is known as the pellet type.

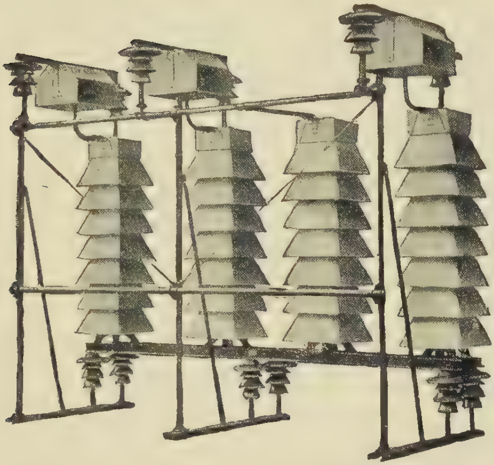


Fig. 105. Type OF, Form BO Oxide Film Arrester — Outdoor Service, Three-phase — 69,300 to 73,000 Volts.

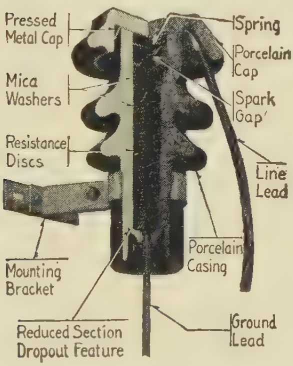
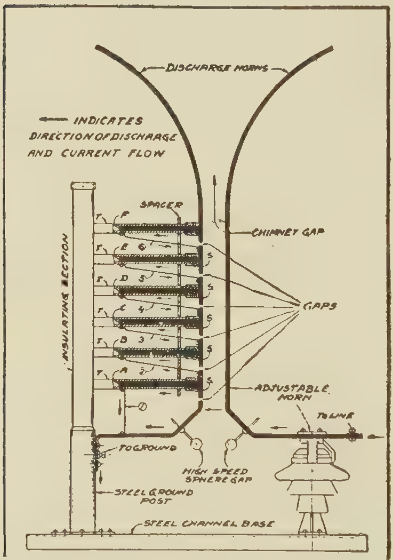


Fig. 106.

Another porcelain tube arrester known as the "auto valve" has an air gap in series with a stack of disks of brass alternating with a thin insulating medium which forms an effective resistance to the flow of line current. The general external appearance of arresters of this type is seen in Fig. 106.

The horn gap arrester is used to a limited extent for the protection of transformer installations supplied direct from a transmission line in rural districts or in villages served from such lines. The arc is extinguished by the flaring horns which gradually increase the length of the arc to the breaking point. The rush of current when no resistance is provided is usually sufficient to open the line circuit breaker, and this limits the usefulness of this type of discharge point. It is usually provided with resistances where its use is necessary. In a large system, the presence of open arcs such as those produced at the horn gap is quite likely to cause pressure rises elsewhere in the system which may endanger apparatus and interfere with service. A special form of horn gap arrester with resistances attached is illustrated in Fig. 107.



Diagrammatic Sketch Showing Elements and Connections.

A = No. 1 Resistance 1 = Ground Lead
B = No. 2 " 2 = Connects A & B
C = No. 3 " 3 = " B & C
D = No. 4 " 4 = " C & D
E = No. 5 " 5 = " D & E
F = No. 6 " 6 = " E & F
"T" indicates insulating tubes.
"S" " copper segments.

Fig. 107

Location of Arresters. — The problem of placing arresters on distribution circuits where they will be most effective, and the determination of the proper number to use in proportion to the apparatus protected is a difficult one. The fact that a discharge will take the nearest path to ground rather than follow the line a few hundred feet to go across the gaps of a lightning arrester is now quite well established. The presence of an arrester within 300 feet of a transformer or cable pole is often of no value in saving the insulation from puncture and destruction. The arrester must be on the same pole with the transformer in order to assure protection of the unit in a severe lightning storm.

The effect of placing an arrester on the transformer pole as compared with arresters placed elsewhere has been studied throughout a period of years by the engineers of several large central station systems, the most extensive study having been made in Chicago.

In sections where an arrester was provided for each transformer and cable pole the loss of transformers from lightning was reduced to a small fraction of one per cent per annum, whereas, in other districts having arresters spaced at intervals of about 1500 feet the losses were 2 per cent in bad lightning years and about 1 per cent as an average.

The cost of arrester equipment is justified for each transformer of size larger than 15 kw. as a means of property insurance, and all such transformers should be protected in regions where lightning storms commonly occur.

It was found in the course of the experiments that the use of arresters at the transformer also greatly reduced the number of primary fuses blown during lightning storms. This has so great value as a means of improving service that the use of arresters for each transformer installation has been made standard practice in some of the larger systems.

On transmission circuits, the use of arresters is usually lim-

ited to substations, cable terminal poles, and transformer installations where such are made at points along the line. It is not desirable to attempt to protect the line itself from lightning in most cases. Insulators have been safeguarded in some cases by the use of an arcing ring or ground rod, the purpose of which is to give the arc an opportunity to go to ground without damaging the insulator. The short interruptions due to the operation of the arcing gaps are found less objectionable than the more extended interruptions due to damaged insulators.

In districts where several towns are supplied by out-of-door transformer installations, the use of arresters is necessary at each installation.

CHAPTER IX

OVERHEAD CONSTRUCTION

Supporting Structures

The use of overhead construction is an economic and practical necessity in a large part of the territory supplied in every city. The investment per kilowatt of maximum load for overhead lines is from 15 per cent to 30 per cent of that required for underground construction and it is obvious that overhead construction must be used for as much of the distributing system as is feasible in order to keep the investment within profitable limits.

Overhead construction is, therefore, very generally used in the outlying parts of the larger cities and in all parts of smaller cities. It is usually not feasible to use overhead construction in congested business districts, as there is not room for the equipment in many cases, and its appearance is objectionable. In many cases the objection to overhead lines may be greatly minimized by locating them in alleys.

The use of overhead lines began with the earliest lighting systems which were installed for street lighting.

Poles and cross arms had been used for the support of overhead lines for many years in connection with telegraph work, and it therefore only remained for the electric lighting engineers to make slight modifications in the spacing of the wires and in the type of insulator employed.

Poles. — The usual form of overhead construction in American practice consists of wooden poles with the wires carried on cross arms.

The woods which are best suited for pole work in America are the Northern white cedar, Western red cedar, chestnut and pine. Other woods are used, but to a limited extent.

White Cedar. — This grows with a natural taper of about 1 inch in diameter to every 5 or 6 feet of length, except near the butt of the pole, where it flares out somewhat larger, making a very substantial and rigid pole. The sapwood, which is about 1 inch thick, is soft enough to make the use of spurs very easy in climbing. The surface of the pole is comparatively free from knots and it is lighter than chestnut or pine.

This species of cedar grows in the region about the Great Lakes and when used in the north central part of the United States has a life of 15 to 25 years, without treatment.

The trees are cut in fall and winter and seasoned several months before shipping, as they lose materially in weight in the first few months by evaporation.

The National Electric Light Association specification for the dimensions of this type of poles appears in the following table.

Circumference of white cedar poles.

Length.	Class *A*.		Class *B*.		Class *C*.	
	Top.	6 ft. from butt.	Top.	6 ft. from butt.	Top.	6 ft. from butt.
25	24	37	22	32	18.75	30
30	24	40	22	36	18.75	33
35	24	43	22	39	18.75	36
40	24	49	22	43	18.75	40
45	24	50	22	47	18.75	43
50	24	53	22	50	18.75	46
55	24	56	22	53	18.75	49
60	24	59	22	56	18.75	53

The dimension 6 feet from the butt is essential with the type of pole because of the fact that the butt often flares con-

siderably, making a butt measurement an inaccurate gauge of the strength of the pole.

It is usual to reject poles having a bend in more than one plane, or any crook which will make it unsightly or difficult to line up with other poles. Poles should not have a sweep in one plane of more than about 12 inches.

Chestnut. — The supply of chestnut timber for poles is found in the New England States, and in the states including the Appalachian range as far south as North Carolina.

The forests are reproducing to a considerable extent due to the fact that the stump of the tree sprouts and grows more rapidly than the seedling. The growth of the tree requires about 40 years from the sprout and 50 years if grown from the seed.

It is considered most desirable to cut the trees in fall and winter as this produces more vigorous sprout growth. Further, as with other woods, seasoning takes place more gradually and with less tendency to produce checking in the pole.

	Circumference in inches.					
Length of pole.	Top.	6 ft. from butt.	Top.	6 ft. from butt.	Top.	6 ft. from butt.
25	24	....	22	....	20	30
30	24	40	22	36	20	33
35	24	43	22	40	20	36
40	24	45	22	43	20	40
45	24	48	22	47	20	43
50	24	51	22	50	20	46
55	24	54	22	53	20	49
60	24	57	22	56	20	....
65	24	60	22	59	20	....

The tree should be cut near the ground in order to include the flaring portion of the trunk in the butt of the pole.

The chestnut pole is considerably heavier than cedar poles

of similar dimensions, and is more likely to have knots which affect its appearance unfavorably. The sapwood is thinner and harder than that of cedar and it is therefore somewhat less adaptable to the use of spurs in doing line work. Its somewhat greater density also seems to be responsible for a somewhat lower insulating value in damp weather.

The dimensions of chestnut poles are shown on p. 231.

Western Cedar. — This is found chiefly in Idaho and Washington, and is used very generally for poles in the western part of the United States. The trees are cut preferably when the sap is down, and are trimmed and peeled immediately in order to facilitate seasoning. The poles are hauled and piled until ready for shipment except where streams are available as in the Puget Sound district. Here they are kept in fresh water until shipped. If kept in salt water for more than 30 days they are attacked by the teredo.

The Western cedar grows with less taper than the Michigan white cedar, it having about 1 inch decrease in diameter, for each 9 feet of length when measured from the butt end. Its weight is approximately the same. Western cedar grows straight and quite clear of knots and twists and presents a neater appearance than any other kind of wood pole.

The dimensions should be specified as follows:

	Circumference in inches.					
Length, feet.	Top.	6 ft. from butt.	Top.	6 ft. from butt.	Top.	6 ft. from butt.
25	28	34	25	31	22	28
30	28	37	25	34	22	30
35	28	40	25	36	22	32
40	28	43	25	38	22	34
45	28	45	25	40	22	36
50	28	47	25	42	22	38
55	28	49	25	44	22	40
60	28	52	25	46	22	42
65	28	54	25	48	22	43

Pine. — There are several varieties of pine which are available for pole work, but none of them are as satisfactory as cedar or chestnut, all things considered.

The loblolly pine which grows in the southern states has many limbs and thus makes a knotty pole, which is not as pleasing in appearance as cedar. If grown in a thick stand it has too little taper to be strong at the butt.

The yellow pine as found in the western states is used in regions where it grows to some extent. The hill grown timber is the better as it is stronger and finer grained because of the slower growth. Valley grown yellow pine is knotty and not well shaped for pole purposes.

Lodgepole pine is also available in the western states. It is similar to yellow pine in respect to knots and is likely to be very slender at the butt if cut from thick stands.

All pine poles should be given a treatment of wood preservative, before being set, as their natural life is very short — less than five years in many cases.

This limitation is aggravated when the poles are set in a climate and soil which differ materially from that in which they have grown. The use of pine poles is therefore limited largely to localities where they are to be had at small expense.

Pole Defects. — All kinds of wood poles have certain natural defects which necessitate a rather careful inspection at the time of purchase or delivery.

Butt rot is common in cedar poles and is likely to occur in chestnut and other woods. It is not a serious defect unless it affects half or more of the diameter, or is so extensive as to reach up into the heart of the pole above the ground line. The presence of heart rot may be noted by an examination of the knots. If the knots show decayed centers it is probable that the heart of the tree is decayed and the pole therefore

weakened. No poles should be accepted which have rot in ring form or which are not sound at the top.

The checking which takes place in connection with the seasoning process may be sufficient to weaken the pole if it takes circular form, and involves a considerable part of the circumference of a circle. Cedar sometimes grows with a twist in the fiber. This is sufficient to affect the strength of the pole if it is so great as to make a complete turn about the axis of the pole within a length of 20 feet or less and such poles should be rejected.

Cedar poles have scars known as " cat faces " at points where the bark of the tree has been injured. If the cat faces are large they weaken the pole and it should be rejected. It is also desirable to avoid using poles having cat faces near the top or at the ground line. Fire-killed poles should not be accepted unless it is evident that they were cut before any decaying process had affected the strength of the wood.

Preservation of Poles. — The life of poles is fixed by the rate of decay of the surface wood at the ground-line. The continuous presence of moisture and air at that point is favorable to the growth of fungi which consume the sapwood quite readily, and, in some localities, the life of the pole is not over 5 to 10 years. Cedar poles have a longer life than pine or cypress, and in the Middle Northern States usually last from 15 to 20 years if not disturbed sooner by reconstruction work. Northern cedar, having heavier butts than Western cedar, has a smaller percentage of sapwood for equal initial strength, and tends to last longer than Western cedar on this account.

This handicap is offset by the treatment of the butts of Western cedar, pine, and other woods with a creosote wood preservative. Such treatment, if so applied as to permeate well into the sapwood, greatly retards the processes of decay

at the ground-line and so materially increases the life of the pole.

In Southern States it is found desirable to impregnate the entire pole in many cases, because of the damage to poles caused by insects of various kinds, when not so treated.

The butt treatment is applied by dipping the butt into a tank of hot preservative and allowing sufficient time for the heat to drive off any residual moisture, and for the preservative to soak into the sapwood to a depth of about one inch.

Preservative is also sometimes applied at the ground-line by means of a brush. This gives a very thin layer of impregnation, which is perforated by surface bruises, such as are common in handling, and its effect is necessarily lost after a few years.

The failing supply of wood poles imposes a duty upon all users of such poles to employ some form of treatment which will give the longest life which can practicably be secured.

Steel Poles. — Where especially great strength and reliability are required, as in the yards of electrified steam railways, at the ends of long spans over streams, and where appearances require something better than wood poles, the steel pole has been quite generally used.

For street lighting in residential districts where arc lamps are employed, the tubular type of pole with 3 to 4 inches butt is used. This is usually done as a matter of appearance.

The tubular pole is made in two, three or four sections, each one being welded to the larger section which overlaps it at the lower end. Three-section and four-section poles are used for heavy corners and ends where there is no possibility of guying to support the strain.

Two-section poles are made in standard sizes of 3 to 13 inches at the butt and in lengths of 22 to 30 feet inclusive. The minimum size of three-section poles is 4 inches at the butt

and they are made in lengths of 24 to 39 feet. Four-section poles are not less than 8 inches at the butt and range from 35 to 40 feet in length.

The lattice type of pole is used where lengths of more than 35 feet are required. This is usually the case in carrying transmission lines along important railroad rights of way and

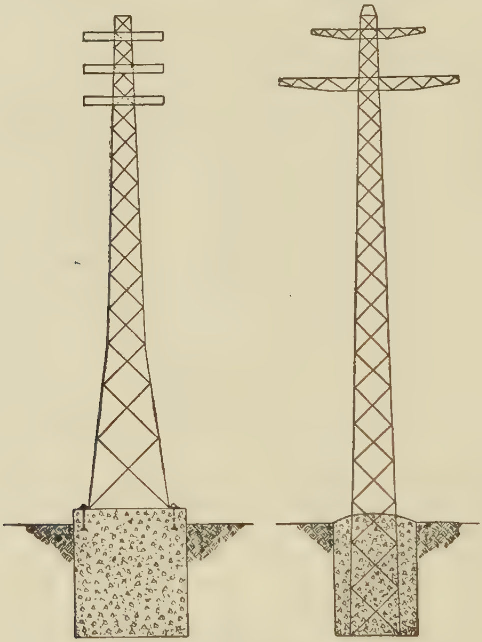


Fig. 108. Steel Poles.

in cases where long spans and high poles are necessary to clear streams.

The requirements of the case vary materially with local conditions, and no standard design is used except with certain patented types of poles in which various lengths are made according to a single type of construction.

The space available for foundations is to a large extent a

governing consideration. Where there is ample space the lower part of the pole may be given a greater amount of flare, thus increasing the stability and reducing the weight of the component parts of the pole. On the other hand, if the base must be made narrow, the steel must be heavier. Much depends also upon the availability of guys. Where suitable guys can be installed the pole may be much less rigid than where it must sustain the stresses by its own strength.

Two types of lattice work poles which have been used in American practice are illustrated in Fig. 108. Various modifications and extensions of these designs have been devised to fill in the gap between the steel pole used for medium high voltage transmission in built-up communities, and the elaborate tower which supports high voltage lines on a private right of way.

Reinforced Concrete Poles. — There is an increasing use of reinforced concrete poles, particularly in sections where the decay of wood is very rapid due to soil and climatic conditions. This type of pole is made either solid or hollow in form, the hollow pole having the advantage of increased strength for the same weight of material.

The solid type, which is most common in American practice, is usually built up in forms laid horizontally. The steel reinforcement should be carefully planned to take both bending and torsional strains. The cross section may be square or circular. In the square form the corners are beveled to improve the appearance and facilitate handling. The concrete must be mixed evenly and applied with care to avoid pockets and to insure every piece of reinforcing metal being thoroughly set to take its share of the strain. In short poles the top diameter may be reduced to 5 inches, but poles of the lengths in common use should be 6 inches or more at the top. The taper should be uniform above the ground-line.

The metal reinforcing parts should be arranged in such a manner as to take the stresses with as little deflection of the pole as possible. In the longer poles it is important that twisted rods or other roughened shapes be used so that the bearing surface under these will be as great as possible. This is especially important with poles which may have to sustain the tension of lines without the aid of adequate guying equipment. The longitudinal members should be well bonded literally to prevent the tendency to buckle.

The concrete mixture which has been found best for pole structures is 1 part Portland cement, 2 parts sand and 4 parts gravel or crushed stone. It must be well tamped and all air bubbles eliminated.

The strength of concrete increases rapidly in the first month or two after mixture, as regards compression. It is therefore desirable that concrete poles be allowed to season 30 to 60 days if possible, before they are subjected to heavy loading. Care must be used in handling while poles are new, to prevent injury to the cement. Long poles should be handled with a crane having two supports for lifting the pole.

The use of concrete poles is not desirable for general distribution purposes, where it is necessary for primary lines to be handled alive, because of the risk to linemen. Their use may be desirable however for transmission purposes where no work is attempted on lines which are alive. The concrete pole should be as strong as a wood pole for similar service and when so made is usually more expensive in first cost than the wood pole. However, its life may be materially longer and its ultimate economy must be determined from a comparison of renewal requirements.

Concrete poles are used for street lighting where a short ornamental pole of the hollow type is employed. This type of pole permits the ready use of underground cable inside the pole and is not expensive in the lengths under 25 feet, as com-

pared with ornamental iron poles. The use of incandescent street lighting by series and multiple systems with relatively small lighting units has greatly evidenced the field of application of the short ornamental concrete pole.

Pole Loading. — Where poles are subject to severe wind and ice loading, it is important that their strength be made equal to the stresses imposed upon them under storm conditions.

These stresses may be carried in part by guying, where space for guys is available, but there are many situations where guying is impracticable and the strength of the pole must be depended upon.

Standards are set by the National Electrical Safety Code for the safe loads which may be imposed on overhead lines. These standards recognize that conditions are more severe in those parts of the United States where ice forms on conductors than elsewhere.

In the states bordering on the Gulf of Mexico, and thence west to California, there are areas in which ice does not form. These areas are designated as those of " light " loading. A narrow zone north of this and the mountain states of the West next form the " medium " loading area, and the remainder is the " heavy " loading zone.

" Heavy " loading is defined as that due to an 8-pound-per-foot wind acting on a conductor while it is coated with ice, having a radial thickness of $\frac{1}{2}$ inch. " Medium " loading is that due to an 8-pound wind with $\frac{1}{4}$ inch ice, and " light " loading is that due to a 12-pound wind without ice.

The force due to a wind of velocity V miles per hour is $P = .002\ V^2$ pounds per square foot when applied to a cylindrical surface, such as that of a bare copper wire or a pole. For a flat surface it is about twice as much as for cylindrical surfaces.

For a 60-mile wind $P = .002 \times 3600 = 7.2$ pounds per

square foot, or, for a pressure of 8 pounds, $V^2 = \frac{8}{.002} = 4000$ and $V = 63$ miles per hour.

In determining the maximum wind velocity for any locality from weather bureau records, it should be noted that the maximum velocities so recorded are usually about 25 per cent higher than the velocities experienced at elevations of 30 to 50 feet above the surface, since the official observation points are usually 100 feet or more above the surface.

The presence of high winds when there is ice on conductors is very rare, but ice formations heavier than $\frac{1}{2}$ inch are common, and the combination is taken as the equivalent of heavier ice loading.

Where there are four or more wires on the same arm, there is a tendency for the wires on the windward side to shield the other wires, thus reducing the wind pressure on them. It is, therefore, provided by the rules of the Safety Code that when more than 10 wires are carried on a pole, the effective area of the wires may be taken as $\frac{2}{3}$ the total area in determining the force exerted by the wind on the pole or supporting structure.

Strength of Poles. — The strength of a pole which is not sustained by guying should be sufficient to withstand the forces resulting from an 8-pound wind on the surface of its ice-covered conductors (in heavy or medium loading districts), acting transversely to the direction of the line.

In the case of poles sustained in part by guying, the combined strength of pole and guys must be sufficient to withstand these forces. A pole will withstand the combined forces acting upon it, when the sum of the moments of the forces acting on the conductors and those acting on the pole does not exceed a value $M = .0002638\ fC^3$, when f is the maximum permissible fibre stress of the wood in pounds per square

inch and C is the circumference of the pole at the ground-line in inches.

The moment of the conductor is

$$M_c = P_1h_1 + P_2h_2, \text{ etc., pound-feet,}$$

in which P_1, P_2, etc. are the forces acting respectively on the wires on the first, second, etc. crossarms, at heights h_1, h_2, etc. from the surface.

The values of P_1, P_2, etc. are the product of the wind pressure by the area of the conductor, with ice-covering in a length equal to the average span length at the pole. Thus, if the span at one side of the pole is 120 feet and that in the opposite direction is 110 feet, the average span length is 115 feet. If the conductor with ice-covering has a diameter of 1.5 inches, the area exposed to the force of the wind in a span of 115 feet is $\frac{1.5}{12} \times 115 = 14.4$ square feet.

With an 8-pound wind, the force on one wire is

$$P = 8 \times 14.4 = 115.2 \text{ pounds.}$$

This, multiplied by the number of wires at elevation h_1, is the total force, P_1, due to all the wires at that elevation.

The force acting on the pole itself is that due to an 8-pound wind acting on the area above ground, and the moment of this force is

$$M_P = \frac{PDh^2}{2} \text{ pound-feet.}$$

D, the diameter in feet, is taken as the average of the top and ground-line diameters; h is the height in feet to the top of the pole, and P is the wind pressure in pounds per square foot.

The maximum permissible fibre stress for Western cedar or chestnut is 2500 pounds per square inch, and for Northern cedar it is 1800 pounds per square inch.

The United States Bureau of Standards has issued a table of

maximum permissible moments for poles having fibre strengths of 2500 and 1800, respectively, and these values are given for some of the more common sizes of poles in the following table:

MAXIMUM PERMISSIBLE MOMENTS FOR WOOD POLES

Circum. at ground, inches.	Fibre stress.		Circum. at ground, inches.	Fibre stress.	
	2500	1800		2500	1800
28	14,500	10,400	46	64,200	46,200
30	17,800	12,800	48	72,900	52,500
32	21,600	15,600	50	82,400	59,400
34	25,900	18,700	52	92,700	66,800
36	30,800	22,150	54	103,800	74,800
38	36,200	26,100	56	115,800	83,400
40	42,200	30,400	58	128,000	92,650
42	48,900	35,200	60	142,500	102,600
44	56,200	40,450	62	157,200	113,200

The sum of the moments due to the wires and the pole itself should not exceed the values given in this table.

The diameters of the commonly used sizes of conductors, without ice loading, follow:

DIAMETER OF CONDUCTORS — INCHES

Size.	Bare.		T.B. weather-proof.	
	Solid.	Stranded.	Solid.	Stranded.
A.W.G.				
12	.08	....	.21	....
10	.10	....	.25	....
8	.13	....	.26	....
6	.16	....	.32	....
4	.20	....	.38	....
2	.26	.29	.44	.48
1	.29	.33	.47	.52
0	.33	.38	.50	.62
00	.37	.41	.53	.66
0000	.46	.52	.65	.79
250,000	....	.575	....	.86
350,000	....	.681	....	.98
500,000	....	.814	....	1.11

Illustration. — Assume a Western cedar pole, having spans of 110 feet and 120 feet, respectively, in each direction, without guying. The pole carries 4 cross arms with wires of the following sizes and elevations:

Arm 1 — 3 Solid bare wires # 0	d, 1.33 in.	h, 28 ft.
Arm 2 — 6 Solid bare wires # 0	d, 1.33 in.	h, 26 ft.
Arm 3 — 6 Solid W.P. wires # 6	d, 1.32 in.	h, 24 ft.
Arm 4 — 3 Stranded W.P. wires # 0000	d, 1.79 in.	h, 22 ft.

The diameters include ½ inch thickness of ice, in addition to the conductor and insulation.

The moments of these groups, due to an 8-pound wind, are as follows:

$$\text{Arm 1}\quad M_1 = \frac{1.33}{12} \times 115 \times 3 \times 8 \times 28 = 8{,}562 \text{ lb.-ft.}$$

$$\text{Arm 2}\quad M_2 = \frac{1.33}{12} \times 115 \times 6 \times 8 \times 26 = 15{,}900 \quad ''$$

$$\text{Arm 3}\quad M_3 = \frac{1.32}{12} \times 115 \times 6 \times 8 \times 24 = 14{,}573 \quad ''$$

$$\text{Arm 4}\quad M_4 = \frac{1.79}{12} \times 115 \times 3 \times 8 \times 22 = 9{,}053 \quad ''$$

$$\text{Total } M_c = 48{,}088 \quad ''$$

Since there are more than 10 conductors, this is reduced to ⅔ the total, or 32,060 pound-feet.

Referring to the table, the allowable moment on a Western cedar pole 38 inches in circumference is 36,200 pound-feet.

The heights assumed are those for a 35-foot pole, set 6 feet in the earth. The top diameter of a pole of this length is about 3 inches less than that at the ground-line, which is $\frac{38}{3.14} = 12$ inches. The average diameter of the pole is, therefore, $\frac{12 + 9}{2} = 10.5$ inches, or .875 feet.

The moment on the pole is

$$M_p = \frac{8 \times .875 \times (29)^2}{2} = 2960 \text{ pound-feet.}$$

The total moment due to wires and the pole itself is $M_c + M_p = 32{,}060 + 2960 = 35{,}020$ pound-feet. This load being somewhat less than that of 36,200 pound-feet, allowed for a pole having a circumference of 38 inches at the ground-line, it would be in accordance with the National Electric Safety Code to use a pole of this size.

If this pole were in a light loading zone, with a 12-pound wind and no ice, the moments would be as follows:

$$\text{Arm 1 } M = \frac{.33}{12} \times 115 \times 3 \times 12 \times 28 = 3{,}180 \text{ lb.-ft.}$$

$$\text{Arm 2 } M = \frac{.33}{12} \times 115 \times 6 \times 12 \times 26 = 5{,}920 \text{ ''}$$

$$\text{Arm 3 } M = \frac{.32}{12} \times 115 \times 6 \times 12 \times 24 = 5{,}280 \text{ ''}$$

$$\text{Arm 4 } M = \frac{.79}{12} \times 115 \times 3 \times 12 \times 22 = 5{,}990 \text{ ''}$$

$$\text{Total } M_c = 20{,}370 \text{ ''}$$

$\frac{2}{3} \times 20{,}370 = 13{,}550$ lb.-ft. effective.

The table of pole moments indicates that a pole having a ground-line circumference of 30 inches would be adequate.

For such a pole, in Western cedar, the diameter is $\frac{30}{3.14} =$ 9.5 inches at the ground-line and 6.7 inches at the top, giving an average diameter of 8 inches, or .67 foot.

$$M_p = \frac{12 \times .67 \times (29)^2}{2} = 3360 \text{ lb.-ft.}$$

$$M = 13{,}550 + 3360 = 16{,}910 \text{ lb.-ft.,}$$

which is within the allowable moment of 17,800 for a pole of this size.

The foregoing illustrations apply to classes of lines known as Grade " A " in the National Electric Safety Code. This includes lines operating at voltages above 7500, where they cross railroads or lines of lower voltage, or are in sufficiently close proximity to them to make it possible for the high-voltage circuits to become involved with low-voltage circuits in case of failure of line supports.

Distributing circuits operating at the usual voltages below 5000 are classed as Grade " C," and are permitted to use factors of safety which require 40 to 45 per cent of the Grade " A " requirements.

Selection of Poles. — The poles chosen for service at any point should have sufficient length to permit the wires carried by it to be carried above trees, communication circuits, trolley wires, and, in some cases, above the roof of a garage or other similar building. Where none of these are present, the height must be such as to give suitable clearance above ground to permit traffic to pass under, or along the line, without interference or danger.

Electric supply wires should be carried over and not under wires used for other purposes, and the pole heights for electric supply lines are often fixed by this requirement.

The pole must, of course, have length above the lowest arm to provide for as many arms as are required for the circuits to be carried. This requires space for 2 to 5 arms or more. In general, more than 5 arms are not required, except for poles near a station where many circuits are brought out overhead. The use of underground lines is often resorted to in such situations to avoid the excessive loading of poles near stations.

Where distribution lines are carried jointly with telephone

circuits, as is the case in many cities, the space is apportioned to each company for its standard distribution equipment, and, in addition, a clearance space of 4 feet between the two is left as a safe working space for construction men. On poles on which a transformer is to be placed, the additional space taken usually requires the use of a pole one size longer than the poles in adjoining spans.

Where trees are encountered, the pole is made long enough to carry the wires above them, unless the trees are very large and have heavy lower limbs with little under-foliage. In such cases it is sometimes preferable to use short poles and string the wires between the larger limbs, using tree insulators as necessary.

On city streets, where electric distribution circuits are carried without telephone circuits, the minimum length of pole is 30 feet. Where jointly occupied with telephone circuits, the minimum size is 35 feet.

At crossings over communication lines and railroads, poles of 40 to 50 feet are commonly found, and, in some cases, 60-foot poles are required.

The use of higher poles should be limited to those places where conditions require them, both because of their additional cost and because of the greater hazard to the line during storms.

The top diameter of poles is determined by the load carried and the amount of sidewise forces or unbalanced tension, to which it is normally subjected.

In small towns or rural sections, where poles carry only local distribution wires of small size and there are not more than 1 or 2 service connections per pole, sufficient strength is afforded by poles having a circumference of 18 inches at the top.

In more densely settled districts, service connections are more numerous, wires are heavier, and poles must be stiff

enough to sustain these loads without serious deflection, and 22-inch top circumferences are commonly used for such service.

For poles carrying transformers larger than 7.5 kilowatts and for corners and dead-ends, where not all the force can be sustained by guying, top circumferences of 25 and 28 inches are generally used.

Western cedar requires a top circumference about 3 inches greater than Northern cedar for similar loading. This is due to the small taper of Western cedar, which gives a slender pole, which is more easily deflected under a given load than a Northern cedar pole of the same top circumference.

Location of Poles. — Poles should be placed in approximately equal span lengths close enough to keep the sag within safe limits and to provide a sufficient number of points at which service drops may be taken off. They should be so spaced that each block section of thoroughfare will be divided into approximately equal span lengths. The spans near self-supported corner poles should be shorter, in order to relieve the strain on the corner pole.

On streets locations should be selected as near lot lines as possible and in such manner as to avoid driveways and entrances. In alleys, access to garages must not be blocked, and where buildings are more than one story high poles should not be placed where they will afford means of access to intruders through windows or over roofs.

Cable poles should be located where the probability of moving at some later date is a minimum, as the cost of moving a cable pole with its pipes and cables is many times as great as that of moving a pole which carries no underground connections. This is also the case, to a smaller degree, with poles carrying heavy transformer installations.

Some of the more common situations met with in the lo-

cation of poles are shown in Fig. 109. In the block south of Broad Street and west of Third Street, the poles in the alley are placed at lot lines and clear garages. The span at the junction pole is shortened to 50 feet, and the junction pole is self-sustained by a concrete support at the ground-line. The transformer and junction poles have 25-inch top circumferences.

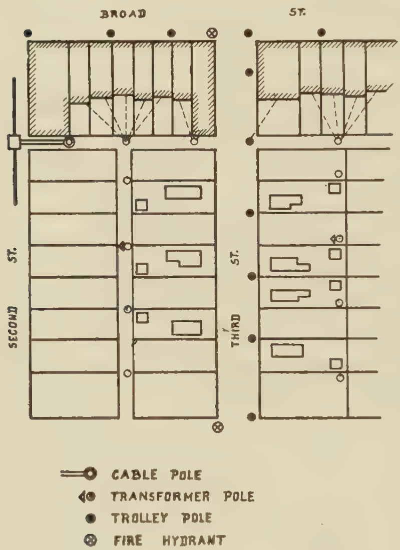


Fig. 109. Location of Poles.

The stores on Broad Street are served from the alley line, but the trolley poles are so placed as not to interfere with entrances, fire hydrants, and other necessary uses of the street as a thoroughfare.

In the block east of Third Street, the garages are reached by driveways to the front. Here the poles on Third Street are set so as to clear the driveways, as well as the entrances of the residences. This line being a part of a through-line, the houses are served from poles set at the rear lot lines, where they clear garages and do not obstruct the owners' premises. Such lines must, of course, be laid out with the coöperation of property owners.

A cable pole connection is shown at Second Street, south of Broad Street, to illustrate conditions where the through-line is underground, and supplies the overhead alley lines at intervals. This pole is set well back from the street, near the corner of the building, where it does not obstruct windows, entrance, or fire escape attachments.

Pole Painting. — The good appearance of poles in public thoroughfares is usually of such importance that it is considered good policy to carefully shave all poles, to remove knots and bark and then give them two coats of paint. A dark green color is very commonly used because of its harmony with foliage in residence districts.

Pole Steps. — All poles which are likely to be climbed to any extent, such as transformer poles, junction poles, poles carrying fuse boxes or other accessories, should be provided with pole steps. This expense is justified in view of the injury done the surface of the pole by the climbing spurs of linemen in the course of time. Pole steps are commonly spaced from 30 to 32 inches apart, alternately on opposite sides of the pole.

It is the practice in most of the larger cities, where poles are used to carry the wires of two or more companies, to provide steps on all poles.

Hub Guards. — Poles which stand at the corner of a street or alley where they are subject to abrasion by the hubs of passing vehicles should be protected from injury by the attachment of hub guards to the pole at the point where abrasion of the pole is likely to occur. It is also necessary in much traveled locations to attach a similar guard about 6 feet from the ground where the box of the vehicle may scrape the poles.

The guard usually consists of a piece of plate iron one-eighth inch thick bent to the approximate curvature of a pole and secured by suitable spikes driven through holes drilled in the iron for this purpose. See Fig. 110.

Gains. — The pole should be cut for the reception of the cross arms before it is erected. These incisions, called gains, shown in Fig. 111, should be about ½ inch deep and of the

necessary width to receive the arm. The distance between centers must be sufficient to give clearance for buck arms and service drops and allow a safe working space for linemen.

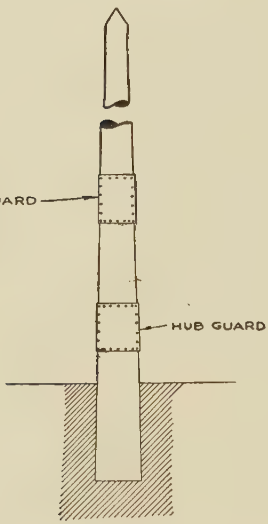


Fig. 110. Hub and Box Guard.

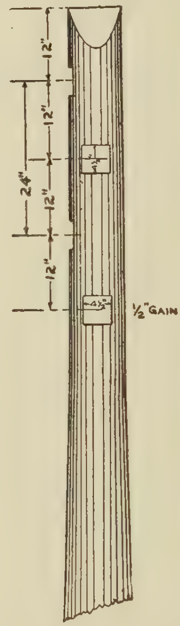


Fig. 111. Gains.

The space usually allowed is therefore 22 to 24 inches, preferably 24 inches between gains.

Pole Setting. — The depth at which poles are set must be such that the normal strains in any direction will not pull the pole out of line. Experience has proved that the following practice is conservative for poles in a straight line:

Size pole...	30	35	40	45	50	55	60	70
Depth.....	5.5′	6′	6.5′	6.5′	7′	7′	7.5′	8′

Corner poles should be set about 6 inches deeper than the above.

The character of the soil and the diameter of the butt of the pole affect these figures in some cases.

For instance, a Western cedar pole with a small butt set in a sandy soil or swampy soil will be much more likely to pull over than a Northern cedar of the same height with a heavy butt, and more depth should be provided for it. In rocky soil where bowlders may be tamped about the pole they need not set so deep.

The pole should be so placed as to bring the natural bend of the pole into the line and should be set erect except at corners, where a slight rake may be given in a direction opposite the strain. Several tampers should be employed to one shoveler in filling the hole, as the thoroughness with which tamping is done while the hole is being filled is an important factor in the stability of the pole. Water may be used to settle the earth where it is available

Where swampy soil is encountered, or in quicksand, the sinking of the hole may be accomplished by the use of a sand barrel. This consists of a sheet-iron cylinder about 30 inches in diameter and three feet long, which is separable into two parts lengthwise. After the hole has been started the barrel is set into it, and as the earth is removed it slips down, preventing the sides of the hole from caving in. After the pole has been erected the barrel is withdrawn and removed by loosening the separable attachments.

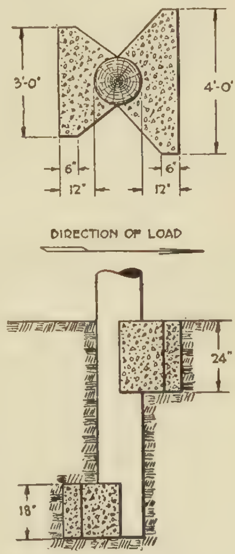


Fig. 112. Concrete Pole Support.

In case the earth filling does not give sufficient stability in such soil this may often be secured by the use of a concrete filling from 6 to 10 inches thick at the

base of the pole and at the ground-line. This has the effect of increasing the bearing surface of the pole and will often prevent the gradual pulling out of line which takes place in such localities.

At corners, bends and dead ends which cannot be properly guyed for any reason, the pole carrying the strain must be self-sustained. This may be done by the use of a concrete filling as shown in Fig. 112.

Guying. — At all points where the direction of a line changes, the tension of the wire should be supported if possible by guying equipment of such strength and design as will

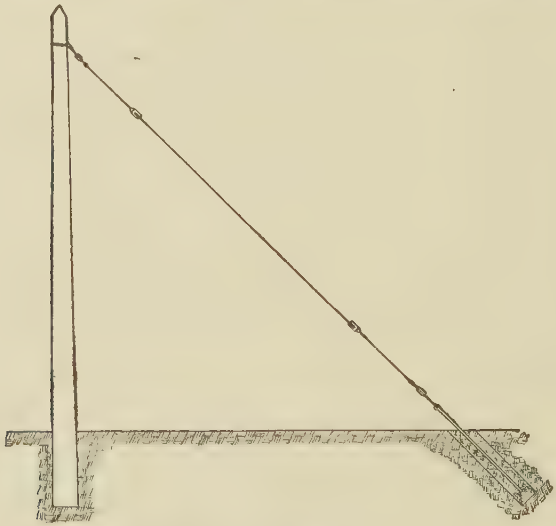


Fig. 113. Anchor Guy.

insure the permanent stability of the pole line and its accessory equipment.

Guy wires are secured at the ground in various ways, depending upon the space available and the clearance required.

Where there is nothing to prevent the guy wire being brought down to the ground near the poles the guy cable may be secured to an anchor as shown in Fig. 113.

Where trees of sufficient size to hold lines without swaying are available they may be used sometimes as anchors. Other fixed objects, such as large rocks and buildings, may also be used in special cases. The location of corner poles on public thoroughfares is often such that guys cannot be run directly to anchors without interfering with traffic. Under such circumstances the guy must be run to a pole known as a stub, where it is attached at such a height as to permit free

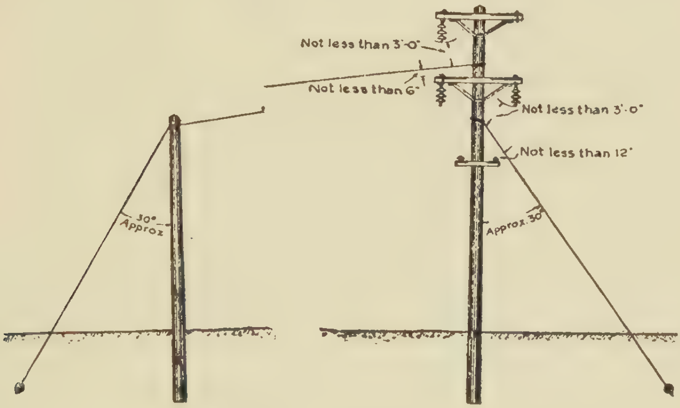


Fig. 114. Stub Guy.

passage under it. It is usually required that guys over roadways should clear the crown of the road about 18 feet, and those over pathways should clear at least 12 feet.

This class of attachment is illustrated in Fig. 114.

The stub is sometimes made self-supporting where the use of an anchor is not practicable or where the height of the stub is not over 15 feet.

On lines which carry three or more cross arms it is important to attach guys on the pole at two points so that the strain

will be distributed and the pole will not be gradually bent out of shape.

Where side arm construction is used it is necessary to support the arms as well as the pole at corners and ends by means of guys attached to eyebolts in the arm, Fig. 115.

At heavy corners which are guyed to stubs or anchors and at self-sustained corners a " head " guy may be used to good advantage. It is run from the base of the corner or end pole to the upper part of the next pole in the line. If the line

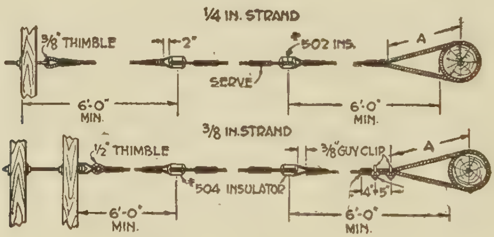


Fig. 115. Arm Guys.

wires are well secured at the poles next to the corner the tension in the corner spans may be reduced, thus relieving the strain on the corner pole.

In straightaway lines the head guy is used to limit the extent of damage in case several poles go over in a wind storm. The head guys on long lines are placed at intervals of about 20 poles. Similarly where a long span exists which is likely to become crossed and burn open, head guys should be maintained at each side to support the line each way in such an emergency.

A typical use of the head guy is illustrated in Fig. 116.

Generally speaking the head guy is a useful means of securing reserve or auxiliary guying for the other forms of guys. Terminal poles, corner poles and jogs in the line may often be head-guyed to advantage.

Guy Cables. — Steel wire or cable is generally employed for guying purposes because of its high tensile strength. It should always be galvanized, since the value of the guy is largely dependent upon its durability and reliability, and

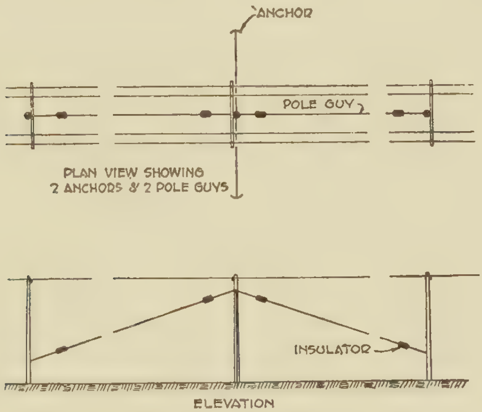


Fig. 116. Head Guying.

plain steel wire is subject to rapid corrosion which steadily weakens it. The stiffness of steel wire is such that it is very difficult to bend it in securing the ends in sizes above No. 8 B.W.G. without impairing its strength. It is therefore used most generally in the stranded forms for guying purposes.

Two sizes of stranded cable are commonly used for guying work, viz.: one-fourth inch having an ultimate tensile strength of 2300 lbs. and three-eighths inch having a strength of 5000 lbs. The 2300-lb. wire is used for the support of lines having one cross arm only and for guying single arms in side arm construction. Larger lines and heavier strains are commonly carried by the 5000-lb. size.

The properties of standard steel strand are as follows:

Area, square inches.	Diameter, inches.	Weight per 1000 ft.	Ultimate strength, pounds.
.144	$\frac{1}{2}$	510	8500
.121	$\frac{7}{16}$	416	6500
.080	$\frac{3}{8}$	295	5000
.064	$\frac{5}{16}$	210	3800
.035	$\frac{1}{4}$	125	2300

Three special grades of galvanized steel strand are also made for special purposes. The Siemens-Martin strand is about 40 per cent stronger than the standard strand. High Strength or Crucible Steel strand is more than twice as strong as standard while Extra High Strength Plow Steel strand is about three times as strong.

These are used only where great strength is required with a minimum weight, as in catenary construction or in making very long spans.

Calculation of Size of Guy Cable. — The pull on a pole due to the tension of the wires having been calculated from the size of the wires, their deflection and span lengths, the tension on the guy wire is equal to the sum of the tension of all the line wires multiplied by the length of the guy wire and divided by the horizontal distance from the pole to the point where the guy wire is attached to the anchor or stub.

Having calculated the tension in any case the size of guy cables should be such that the strain will be from $\frac{1}{4}$ to $\frac{1}{5}$ the ultimate breaking strength of the cable.

For instance, with a line carrying 18 wires at a tension of 150 pounds each, supported by a guy cable 40 feet long, with the anchor attachment 30 feet back from the pole, what size of guy cable should be used? The total line wire tension is 2700 pounds, and the guy cable tension is therefore $\frac{2700 \times 40}{30}$

= 3600 pounds. This would require the strength of two 5000-lb. cables to support the strain.

In case the anchor were but 12 feet back from the pole, the cable would be about 36 feet long, and the tension on the guy would be $\frac{2700 \times 36}{12}$ = 8100 pounds.

This would necessitate the use of two 5000-lb. cables attached to the anchor, and a head guy of $\frac{3}{8}$-inch cable to the first pole back from the terminal pole. The head guy, acting at a more favorable angle, could be adjusted to carry a part of the strain. An anchor should not be placed nearer to a pole than one-quarter the height of the guy attachment on the pole.

Attachment of Guys. — In making attachment of a guy cable to a pole or stub it is given two turns about the pole

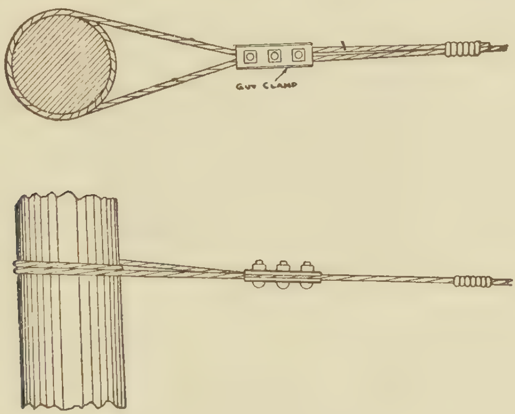


Fig. 117. Guy Clamps.

and the end brought back and well secured. The smaller sizes may be secured at the ends by wrapping, but the larger sizes are preferably fastened by means of clamps. When an anchor having an eye at the upper end is used the cable should

be protected by a thimble to avoid too sharp a bend at the point where all the strain is carried.

The method of applying clamps which are bolted and of securing the end of the guy cable is illustrated in Fig. 117.

When guys are attached to a tree, the tree should be protected by the use of a bolt through the tree. It is desirable with heavy guys to put protecting strips under them when wrapping the cable about the pole. This is not so necessary with chestnut and other timber having hard sapwood. Strips of galvanized plate iron about 2 inches wide are commonly used for this purpose.

Strain Insulators. — The proximity of guy cables to primary wires affords opportunity for leakage in wet weather and renders them subject to accidental crosses with live conductors at times. It is therefore important that guy cables be equipped with strain insulators attached not less than 8 feet from

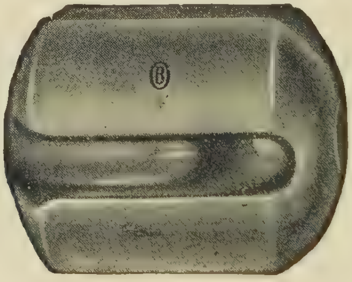


Fig. 118. Porcelain Guy Insulator.

the ground. This precaution is advisable for the protection of the public and of linemen, whose safety is endangered by the presence of grounded guy cables near live wires on which they are working. It is therefore customary to keep guy cables above ground as much as possible and to sectionalize them by the use of two strain insulators of the type shown in Fig. 118. The strain insulators are put in about 6 feet from each end.

The guying equipment should be installed before the wire is strung so that when the tension is applied the corner poles may be pulled up to their normal position.

In supporting the strain of high-tension lines up to 13,200 volts it is customary to employ porcelain strain insulators of the same type, but having larger leakage surfaces.

CHAPTER X

OVERHEAD CONSTRUCTION

Lines and Accessories

Cross Arms. — In the selection of wood for cross arms for distribution work the physical characteristics of the wood must be carefully considered. Longleaf Southern pine and Douglas fir are the best woods, because of their straight grain, high tensile strength and durability. The chief cause of deterioration in cross arms is the alternate action of the sun and rain, which tends to open up cracks on the upper side, allowing water to soak into the wood and creating conditions which are favorable to processes of decay. It is therefore important that the top surface of the cross arms be rounded off so that the water will run off easily.

The timber should be thoroughly kiln-dried before it is worked up as the shrinkage of pin holes in arms made when the wood is green is sufficient to seriously interfere with the fitting of the arm with pins.

There should not be any sapwood in pine or more than 25 per cent in fir arms and this should be on the side or top. The grain should be straight and there should be no knots of such size as to weaken the arm. This requires that there be no knots over $\frac{3}{4}$ inch in diameter in the standard arm. There should be no checks over 3 inches long, no loose hearts, and no worm-eaten or otherwise unsound portions of the cross arm. These requirements are essential to the safety of men working on the line, as well as to the security of the service rendered.

The cross-section should be of such shape and area that the arm will bear the weight of a lineman, in addition to that of

the wires, without danger of breaking. This demands a good factor of safety to provide for proper strength after the arm has become weakened by partial decay. Experience indicates that a cross-section $3\frac{1}{2}$ inches wide by $4\frac{1}{2}$ inches high is ample for the average requirements of distributing lines.

The appearance of a distributing line is best if a uniform length of cross arm is used. In suburban districts main lines are commonly of 6-pin arms with 4-pin arms on the distributing lines.

In city work where both light and power secondaries must be carried on the same arm, it is usually found necessary to use 6-pin arms for distributing lines with 8-pin arms on lines carrying many wires.

Where lines are occupied jointly with other companies it is desirable that arms of approximately equal length be used by each company.

The spacing of pins should be suited to the voltage of distribution, should provide a safe working space for linemen and should take into account the normal sag of the wires. Under the usual working conditions of distributing lines spacings for primary wires should be 14 to 15 inches between centers. In general, the wider spacings are common on 4-pin arms and the narrower on 6-pin. The spacing of pins next to the pole must be such that sufficient room is left for linemen to get up through the lower wires safely to work on the upper arms, at least 30 inches being required between pole pins.

The dimensions and spacings of cross arms shown in Fig. 119 are representative of average practice, minor variations being found in various parts of the country.

In the attachment of cross arms, the arm should be placed on the side of the pole away from the heaviest strain. In a straight line, the arms should be put face to face and back to back in alternate spans. The face of the pole is the side on which the arm is mounted.

Side Arms. — Where alleys are available for distribution lines, a side arm or alley arm is commonly used. This is necessitated by the fact that the poles must be set as near as practicable to the fence or building line, and when cross arms

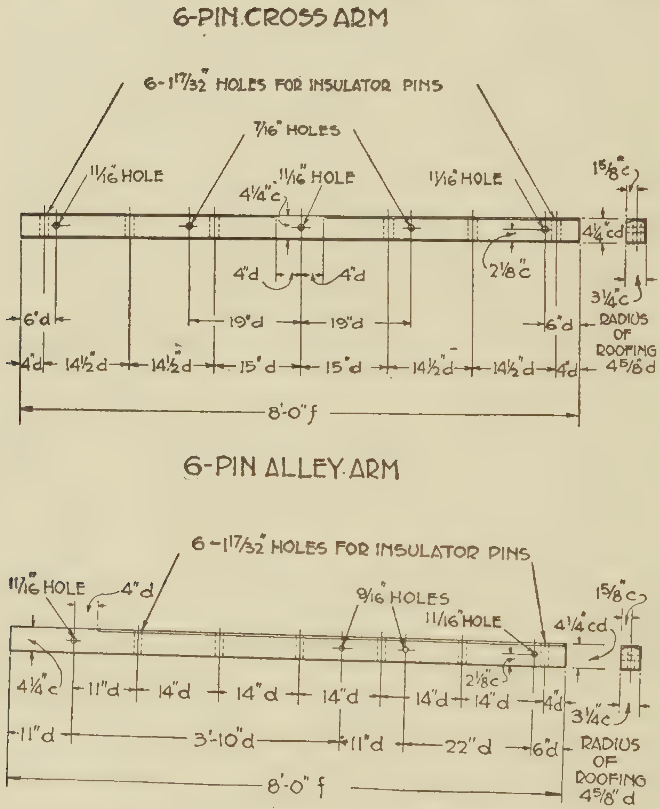


Fig. 119. Dimensions of Standard Arms.

are used, one end overhangs the adjoining property. Where buildings of more than one story are present the wires which overhang must then be carried above the roof by setting higher poles, or be offset by using side arms at points where the line passes such buildings. Either of these plans results in un-

symmetrical construction, and experience has indicated that it is better to make the entire line a side arm line at the time of original construction. Continuous rebuilding is, thus, avoided, and the disadvantages due to side arm construction are not serious.

There are two respects in which side arm work differs radically from cross arm work, viz., guying and arm-bracing.

At dead-ends the guys must be attached to the side arm to carry the tension of the wires to the guy stub, and the guy

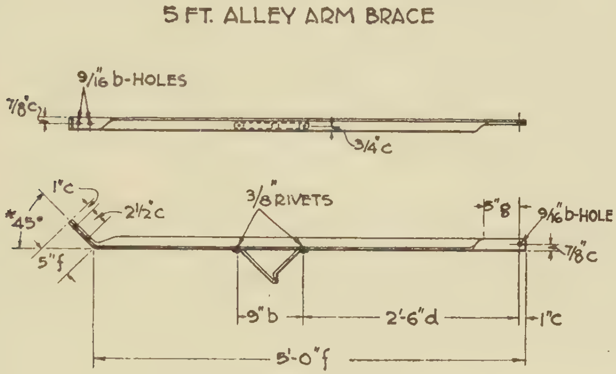


Fig. 120. Side Arm Brace.

cable must have an attachment to each arm. In turning a corner, the guy is attached to the pole as in cross arm work.

The side arm is supported by a brace attached about midway between the pole and the outer end of the arm. This brace must be sufficiently stiff to support the weight of a lineman, as well as that of the wires and arms. Where more than one arm is used, a vertical brace carries the load of the upper arm, or arms, to the bottom arm, whence it is carried to the side of the pole by the main brace, at an angle of about 45 degrees. Side arm braces are, therefore, usually of angle iron, and of dimensions such as those shown in Fig. 120.

Cross arms may sometimes be used for dead-ending such a line if local conditions permit. The service drops are taken off on cross arms placed as "buck" arms, at right angles to the side arms.

The arrangement of circuits on 4-pin and 6-pin side arms is shown in Fig. 121. A 4-pin arm is used for 4-wire primary circuits and the 6-pin arm for secondary mains. The primary

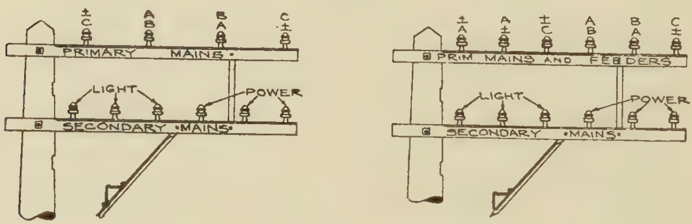


Fig. 121. Wire Arrangement.

arm is made equal in length to the secondary arm, as a matter of symmetry, and this affords additional clearance between primary wires, which reduces the possibility of service interruptions during stormy weather.

Double Arming. — At corners, terminals and other points where there is an unusual strain, the poles should be fitted with a double arm equipment so that the strain will be carried by more than one support.

The arms should be bolted together at the ends with suitable spreaders to fill in the space between them and make a solid structure. This may be done by the use of a block of wood or by spreader bolts having nuts which clamp the arms on both sides, as shown in Fig. 122. It is usual to use $\frac{5}{8}$-inch bolts with either type of spreader, to bind the arms together. Suitable washers should be used to give proper bearing surface between nuts and wood.

The double arm bolt may be provided with an eyelet as

shown in Fig. 122 instead of one of the nuts. This makes a convenient point of attachment for an arm guy cable on terminal poles with side arms.

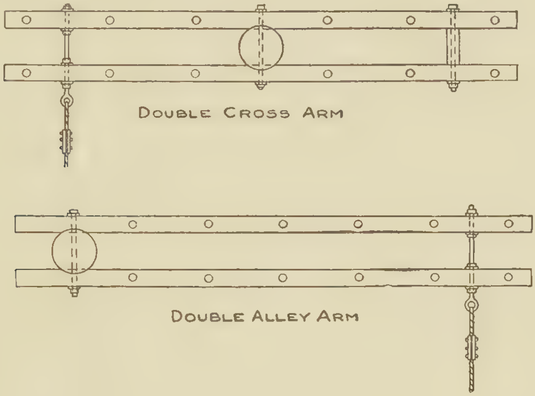


Fig. 122.

An eyebolt is required for this purpose where a side arm is guyed.

Washers of square plate $\frac{3}{16}$ inch thick and 2 by 2 inches are used on cross arm bolts. Circular washers $1\frac{1}{2}$ inches in diameter are used with carriage bolts on braces.

Arm Bolts. — Arms should be fastened to the pole by bolts. The bolt is fitted with a nut and washer on both ends, to give a firm and durable seat for the nut. The bolt should be $\frac{5}{8}$ inch in diameter and from 12 to 16 inches long, depending upon the diameter of the pole.

Arm Braces. — In order to hold the cross arm firmly in a horizontal position, braces must be provided. These are usually of strap iron about $\frac{1}{4}$ inch by $1\frac{1}{4}$ inch by 26 inches to 30 inches long. The brace is placed at an angle of about 45 degrees with the pole and is attached by means of lag screws to the pole and by carriage bolts through the cross arms.

For heavy arms on transmission circuits an angle iron brace is usually employed. This is made in a single piece, bent in the shape of a bow, as in Fig. 123.

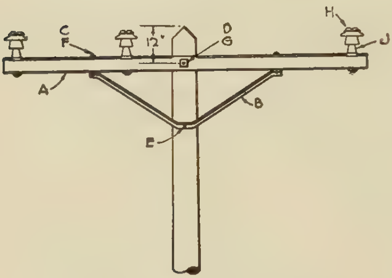


Fig. 123. Angle Iron Braces.

Pins. — Pins of wood are preferred for distribution work on account of their low cost and insulating qualities. Locust, elm, oak and other woods are common, but locust is superior to all in strength and durability.

Only clear, straight grained wood, free from rot or defects which affect strength, should be used for pins, as they are at times subjected to forces of 300 to 500 pounds.

Where wires of # 2 and smaller are dead-ended or carried around a corner it is customary to distribute the strain between two pins by using double-arm construction. With heavier cables it is not desirable to attempt to support the strain by a pin, but it is usual in such cases to insert a strain insulator in the line near the pole and take the strain more directly on the guy cable.

Steel pins are commonly used for transmission lines where the size of the insulator necessitates a pin so long that wooden pins of the ordinary type are not adequate.

The cemented type of pin is made in two forms, solid and with detachable thimble. The solid type must be cemented to the insulator before it is mounted on the arm, and after delivery in the field. The difficulties of handling such work properly in the field led to the development of the detachable thimble. This may be cemented in the insulator at the factory and screwed to the iron pin on the cross arm, thus mounting the insulator as readily as it is done with wood pins. This type

of pin also greatly facilitates the replacement of defective insulators.

Steel pins are secured to the cross arm by nuts and washers on the under side of the arm, as shown in Fig. 124. There

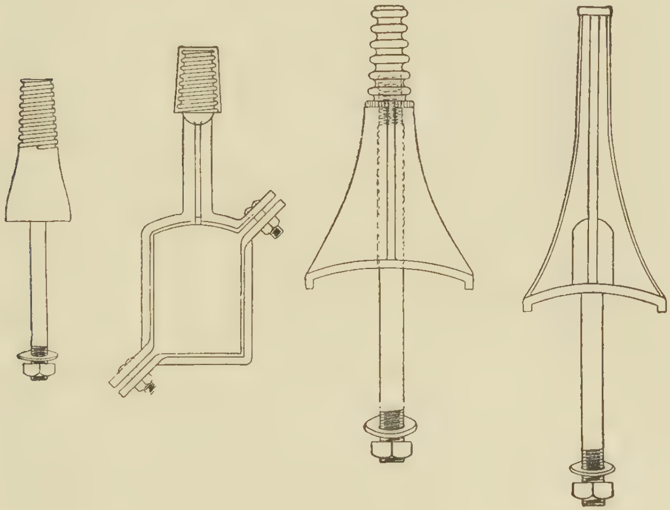


Fig. 124. Steel Pins.

are also certain types which are made in the form of a clamp bolted around the arm, and not passing through it.

Steel pins are used quite generally for the voltages above 10,000, up to about 40,000 volts, above which the suspension type of insulator is generally considered preferable.

The insulator is secured to a steel pin by threads as with the wood pin, or by cementing. In the threaded type, provision must be made for expansion to guard against cracking the insulator. This is done in various ways. In the smaller sizes, a threaded wood thimble is mounted on the iron rod which forms the shank of the pin. In other forms, the threaded portion is slotted and a piece of felt serves as a cushion in the

slot. The threads are made in the form of a spiral spring in another type. This has sufficient flexibility to take up the strains of contraction and expansion.

Insulators. — The most common type of insulator in distribution practice is that known as the deep-groove double-petticoat insulator of glass or porcelain shown in Fig. 125. The dimensions of this insulator are sufficient to carry circuits operating at potentials up to 5000 volts safely with standard wooden pins. The groove is ample for any size of weatherproof wire up to # 00. The line wire is secured to the insulator by a tie wire laid in the groove and twisted around the line wire several times at each side of the insulator. The point of support is relatively low and the side strain on the pin is therefore reduced to a minimum.

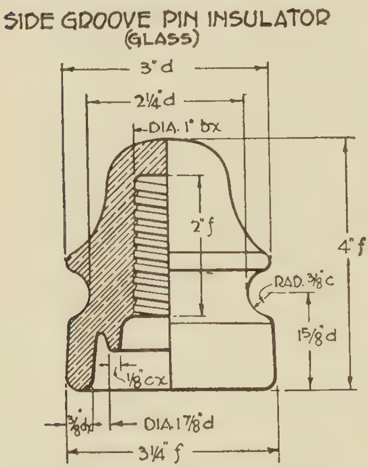


Fig. 125. 2300-Volt Insulator.

The double petticoat is ample protection from leakage of electricity during stormy weather.

The glass insulator is most commonly used for distribution purposes at voltages under 5000. In some cases porcelain insulators are used for primary wires with glass for secondary mains. Others have adopted porcelain insulators having different colored glazing as a means of readily identifying circuits of different classes. This is said to be found effective as a safety precaution where series lighting circuits, power circuits and general lighting circuits are carried on the same poles.

Manufacture. — The manufacture of porcelain insulators is carried on by two processes known as the *wet* and the *dry*. The methods vary also in accordance with the character of the clays which are used and each manufacturer must adapt his processes to the clays which are best suited to the majority of his product. Clays from different sources vary in their electrical, mechanical and chemical characteristics and it is often necessary to use mixtures in order to secure the best product.

The mixture must be thoroughly made in order to produce a uniform quality of porcelain.

In making porcelain by the wet process, the mixture of clays is made with a sufficient amount of water to thoroughly exclude all air. The wet clay is then worked into a rough mold, having the general shape of the exterior of the piece. If it is to have a hollow center, this is roughly formed by a central plunger. The mass being formed while the clay is thoroughly wet, the density of the porcelain is greater, and higher electric resistance is secured as a result. The piece is set aside to dry until it is strong enough to be removed from the mold without danger of distortion. It is then left until quite thoroughly dried, when it is put into a lathe and smoothed up ready for glazing and firing. The parts which are to be cemented are turned sufficiently to insure an accurate fit.

By the dry process, the clay is used in the form of a dampened powder made by pulverizing the dried mass of clay left after the mixing process. This pulverized clay is pressed into steel molds under heavy pressure. The molded piece is set aside to be thoroughly dried before firing and glazing. The steel molds are so accurately made that little finishing work is needed before the glaze is applied.

The glazing is applied by dipping the molded piece of clay into a solution which covers all parts of the clay which are to

be glazed. The clay is then fired at a carefully regulated heat for about 48 hours after which it is allowed to slowly cool before the kiln is opened for the removal of the porcelain.

Wet process porcelain is used for high tension insulators because of its mechanical and electrical strength, while the dry process is preferred for the complicated shapes used in many ways at lower voltages.

Insulators for voltages of over 20,000 are made in two or more pieces, as shown in Fig. 126, which illustrates common designs for use at 20,000 and 33,000 volts, respectively.

Each petticoat of such insulators is formed and fired separately in order to insure greater dielectric strength and avoid

20,000-volt 33,000-volt.

Fig. 126.

the checking which takes place in thick pieces of porcelain during the firing process.

These pieces are then assembled by the use of a suitable cement. Pure Portland cement is quite commonly used and is in most respects the best. Sulphur is strong and a good insulator but, in case of heat from an arc, easily melts and mechanical failure results. Condensite, a substance derived by chemical process, is excellent for the purpose, from the standpoint of electrical and mechanical strength, but is rather expensive.

It is important that the design of an insulator take into account both electrical and mechanical stresses. The shape of the petticoats must be such as to permit a discharge to

flash over before it will puncture, if the number of insulator failures is to be kept at a minimum. It is usual to make the proportions such that the puncture strength is about 1.3 to 1.5 times the flash-over voltage.

Mechanically the insulator must be able to support the tension and weight of the line without crumbling and with sufficient factor of safety to prevent early failures. These features of design are largely matters of experiment and practical operating experience.

Such problems are more apt to be troublesome with tower lines having long spans and heavy conductors than with standard lines on highways.

Wire. — The size of wires is in general determined by the conditions of load, distance, etc., but in overhead work the mechanical strength must be adequate and it is therefore not safe to use wire smaller than # 6 for primary lines. It is also common practice to extend this rule to low-tension lines, though # 8 is sometimes used for short secondary lines. # 8 and # 10 are used for service drops to small consumers quite generally.

For distribution circuits, soft or medium hard wire is employed. Hard wire, that which has not been annealed after drawing, is stronger than soft wire and is often used for transmission circuits where its greater strength is of value in meeting the high stresses in long spans, and where jointing and taps are not frequent.

Medium hard wire is used to some extent for distribution work where additional strength is needed.

The operation of soldering anneals hard or medium wire at the joint, and, thus, tends to reduce the strength at joints to that of soft wire. Mechanical devices, such as sleeves, must, therefore, be resorted to in making joints in hard wire where it is to be under full tension.

Hard wire is also weakened by kinking or scratching and must be handled carefully. It is much stiffer than soft wire.

For these reasons, and because of the frequent necessity for joints and half-taps in distribution circuits, soft wire is used quite generally for such circuits.

For transmission lines, voltages are too high to permit the use of insulation, and bare wire is commonly employed.

Distribution circuits are covered with what is known as "triple-braid weatherproof insulation." This consists of three braids of fibrous insulation impregnated with a bituminous compound, and given an outer coating of a waxy compound to prevent absorption of water. This gives a considerable degree of protection to linemen working on live circuits at voltages up to 4000, and is also of value in other ways.

Weatherproof insulation is commonly used in cities, and insulation is required by ordinance, in some cases, for all wires regardless of voltage.

Solid wire is used in all sizes up to # 0 A.W.G. for distribution circuits. Larger sizes are usually of stranded conductor.

Where strength is of great importance for a long span, stranded conductor is sometimes used in sizes smaller than #0.

Copper is universally used for distribution, and largely for transmission. Aluminum is used to some extent for transmission because of its light weight. It is, however, too difficult to solder to be used for distribution circuits.

Wire Stringing. — In erecting wire it is usual to string the conductors by a rope over the cross arms for a distance of several spans of line. When in place one end is secured and tension applied to the wires separately by the use of block and tackle. When the tension has been correctly adjusted, linemen stationed at several points apply the tie wires, thus

securing the line to the insulators. The remaining wires are similarly drawn up, care being taken to get the tension on all wires about the same. The tension varies with the size of the wire and with the deflection which is considered permissible. It should be made sufficient to prevent too much sag in the spans and yet must not be so great as to unduly strain the wire and the guying equipment which supports it.

Tie Wires. — Line wires are secured to the insulator by means of tie wires or with heavy lines and long spans by means of clamps. Tie wires are used almost exclusively with distributing circuits as they are sufficient to withstand the usual loads found in such work. With weatherproof or other insulated wire, the tie wires should be insulated in order to prevent cutting through the line wire insulation. Annealed wire should be used to insure a tight wrap and the size used for various sizes of line wire should be as follows:

6 tie wire for # 6 or # 4 line wire.
4 tie wire for # 1 or # 0 line wire.
2 tie wire for # 00 or # 0000 line wire.

In straight runs the ties on the pole pins should be applied so that the wires will be on the side of the insulator away from

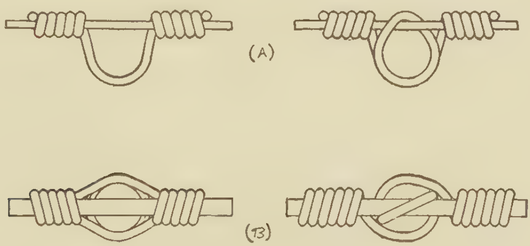


Fig. 127. Ties.

the pole. On the other pins, the wire should be on the side nearest the pole. At corners and bends all wires should be behind the insulator, that is, on the side opposite the direc-

tion of pull. The common method of applying tie wires to insulators having side grooves is illustrated in Fig. 127 (*A*). For the larger sizes of conductors, where the groove is on top of the insulator, the tie shown in Fig. 127 (*B*) is commonly used.

For heavy transmission lines with long spans it is often considered preferable to attach the line wire to the top of the insulator by the use of a clamp such as that shown in Fig. 128. This device is also useful at the ends of long spans or at other points of extra strain.

Joints and Taps. — Joints in line conductors should be carefully made to support the tension of the line and to give good electrical conductivity. They must be soldered to preserve their conductivity and should be taped to an amount equivalent to the insulation of the wire to protect linemen.

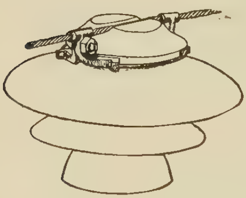


Fig. 128.

Taps must be treated in a similar manner.

With stranded cables a neatly interwoven joint is essential to carry the load.

Where possible, joints should be made at points where the tension is a minimum.

Calculation of Tension and Sag. — The theoretical curve formed by a wire supported under tension as in pole work is known as a catenary. The equation of this curve is based on the assumption that the wire is inextensible and perfectly flexible. This is, of course, not strictly true of insulated copper wire, and it is therefore found sufficiently accurate for all practical purposes to use the approximate formula by Rankine and others as follows:

$$T = \frac{(L)^2 w}{8\,S},$$

in which T is the wire tension in pounds, L is the length of the span in feet, w is the weight of one foot of conductor and insulation, and S is the sag or deflection in feet.

To illustrate, assume a # 6 weatherproof wire carried on poles 100 feet apart, with a sag of 1 foot; what is the tension on the wire? The weight of one foot of # 6 wire being about 0.112 pound, $T = \frac{100 \times 100 \times .112}{8 \times 1} = 140$ pounds. If the spans were 141 feet, the strain would be doubled, and at 200 feet they would have to be quadrupled in order to keep the sag at one foot. If the tension is the same on several spans of different lengths, the deflection will be different in each span. In practical work this is usually the case, as the tension is usually the same throughout any section of line unless special provisions are made for guying certain spans of unusual length so as to increase the tension.

The sag of any span when the tension is known is found by interchanging T and S in the foregoing formula so that it reads $S = \frac{(L)^2 w}{8\,T}$. In the case of a # 0000 wire in a 141-foot span under 1025 pounds tension,

$$S = \frac{141 \times 141 \times .82}{8 \times 1025} = 2 \text{ feet.}$$

The maximum tension in a line is limited by the strength of the wire and its supports. The ultimate breaking strength of annealed copper wire is about 34,000 pounds per square inch, but the working strain should not be over one-quarter of this. If pulled up too tight the wire stretches, increasing the sag and diminishing its cross-section.

For # 6 wire, which has an area of .0206 square inch, the ultimate breaking strength is about 700 pounds. The safe working strain is therefore about 175 pounds, which gives a 14-inch sag in a 125-foot span. The safe working strength of

0000 wire, which has an area of .1662 square inch, is found in a similar way to be 1400 pounds, which gives about 15 inches sag in a 125-foot span.

With hard-drawn wire the ultimate tensile strength is about 60,000 pounds. Such wire is left in the hardened condition in which it comes from the wire-drawing dies, which gives it greater strength and stiffness.

The sag and tension of weatherproof and bare, hard-drawn wire may be readily determined from the figures in the following table for various sizes of wire.

ANNEALED WEATHERPROOF WIRE, 100-FOOT SPAN.

B. & S. G.	10	8	6	4	2	1	0	2/0	3/0	4/0
T at 1 ft. sag	62	92	140	204	318	390	486	607	767	942
S at 100 lbs. tension	.62	.92	1.40	2.04	3.18	3.9	4.86	6.07	7.67	9.42
Weight wire per ft.	50	74	112	163	254	312	388	486	614	754
Breaking stress	283	440	700	1114	1772	2234	2818	3553	4480	5650

HARD-DRAWN BARE WIRE, 100-FOOT SPAN.

T at 1 ft. sag	39.3	62	99	157	161	202	400	505	636	800
S at 100 lbs. tension	.393	.62	.99	1.57	1.61	2.02	4.0	5.05	6.36	8.00
Weight wire per ft.	31.4	50	79.5	126	201	253	320	403	508	640
Breaking stress	500	778	1237	1967	3127	3943	4973	6271	7907	9971

The tension at any other sag, or the sag at any other tension, or the sag or tension in any other length of span, may be readily found from the above table as follows:

The tension at any other sag is $T' = \frac{T}{S}$, in which S is the sag in feet at which the tension is desired and T is the value in the above table in pounds.

For illustration, what is the tension in a 100-foot span of # 0 weatherproof wire at a deflection of 2 feet?

$$T' = \frac{T}{S} = \frac{486}{2} = 243 \text{ pounds.}$$

Similarly the sag at any other tension is $S' = \frac{S \times 100}{T}$, in which T is the assumed tension and S is the value of sag at 100 pounds in the above table. With # 0 weatherproof wire the sag at 300 pounds is

$$S' = \frac{S \times 100}{T} = \frac{4.86 \times 100}{300} = 1.62 \text{ feet.}$$

With spans of other lengths the sag or tension varies in proportion to the square of the length of the assumed span.

That is, $S' = \left(\frac{L'}{100}\right)^2 S$ and $T' = \left(\frac{L'}{100}\right)^2 T$.

With # 4/0 bare wire, for instance, the tension with a span of 150 feet at 1 foot sag would be $T' = \left(\frac{L'}{100}\right)^2 T = \left(\frac{150}{100}\right)^2 \times 800 = 1800$ pounds. Or if the tension of the line were 600 lbs. in all the spans, the sag in a 150-foot span of bare # 4/0 wire would be $S' = \left(\frac{L'}{100}\right)^2 S = \left(\frac{150}{100}\right)^2 \times \frac{8}{6} = 3$ feet.

The foregoing table may be used in the solution of practical problems as follows:

A line of # 2 weatherproof wire is to be strung on poles with spans of 110, 150 and 200 feet at various points. What deflection will result if the wire is pulled up to a tension of 300 pounds on all spans?

The sag at 300 pounds on a 100-foot span is

$$S' = \frac{3.18 \times 100}{300} = 1.06 \text{ feet.}$$

On 110-foot spans, $S' = 1.1 \times 1.1 \times 1.06 = 1.28$ feet.
On 150-foot spans, $S' = 1.5 \times 1.5 \times 1.06 = 2.38$ feet.
On 200-foot spans, $S' = 2 \times 2 \times 1.06 = 4.24$ feet.

If 4.24 feet is considered more deflection than is safe on the 200-foot spans, what tension must be used to reduce this to 2.5 feet?

$$T' = 300 \times \frac{4.24}{2.5} = 510 \text{ pounds.}$$

Expansion and Contraction. — The changes in the sag of lines due to the expansion and contraction of the wires under varying temperatures are of much importance in the erection of the conductors. Lines erected during the summer months are found drawn very tight during the winter months, while those erected during winter months are apt to be too slack during the summer. Allowance should therefore be made for the temperature at the time the work is done.

The length of the wire in any span may be calculated from the approximate formula

$$L' = L + \frac{8\,(S)^2}{3\,L},$$

in which L is the length of span in feet and S is the sag in feet. With a 100-foot span of 1 foot sag,

$$L' = 100 + \frac{8 \times 1}{3 \times 100} = 100.0266 \text{ feet.}$$

That is, the wire is .0266 foot or .32 inch longer than the span. Likewise, if the length of wire is known, the sag is

$$S = \sqrt{\frac{3\,L(L' - L)}{8}}.$$

For instance, if a wire should slip on the insulator so as to add .48 inch or .04 foot to the length of wire in the above span, the sag would be increased to

$$S = \sqrt{\frac{3 \times 100}{8}(100.0666 - 100)} = 1.88 \text{ feet, or 19 inches.}$$

The same condition would result if the pole were pulled over so as to shorten the span .48 inch.

The length of wire in a span varies in proportion to the coefficient of expansion and the range of temperature. $W' = W(1 + at)$, in which a is the coefficient of expansion, t is the range of temperature in degrees Fahrenheit, and W is the length of wire at the lower temperature. When the length of wire at the higher temperature is known and the contraction is to be computed instead of the expansion, the formula is $W = \frac{W'}{1 + at}$, in which W' is the known length at the higher temperature.

The coefficient of expansion of copper wire is $a = .000096$ per degree rise Fahrenheit. This is subject to some variation under the conditions of practical operation due to stretching which affect the accuracy of calculations for the wider ranges of temperature.

For long spans it is desirable to make calculations to get approximately the difference between the sag during the winter and the summer months.

For example, in a line crossing a stream with a distance of 300 feet between supports, the sag was 5 feet at temperature of 25° F. What will be the sag at 95° F.?

The length of wire in the 300-foot span at a sag of 5 feet is $L' = 300 + \frac{8 \times 5 \times 5}{3 \times 300} = 300.222$ feet.

At a temperature of 95° F. the rise in temperature is $t = 70$ degrees, and the length of wire becomes $L' = 300.222 (1 + .000096 \times 70) = 302.239$ feet.

The increase in length is 2.017 feet and the sag, assuming no change in the position of supports, would be

$$S = \sqrt{\frac{3 \times 300\ (302.239 - 300)}{8}} = 15.8 \text{ feet.}$$

Thus the sag would be about 10 feet greater on this span in hot weather than during the winter months if there were no elasticity in the supports. In practice, however, the difference would not be over 6 or 7 feet.

Sag Tables. — The sag given a line when erected should vary, according to the temperature at which the work is done, to allow proper clearances at higher temperatures and prevent over-stressing of the wire at lower temperatures. Fortunately, these effects are both reduced by the flexibility and resilience of poles and supports, so that stresses during severely cold weather are less than the theoretical amount, and sags during hot weather are usually not as great as they would be with rigid supports.

The following table, taken from data prepared by the United States Bureau of Standards for use in connection with the National Electric Safety Code, gives sags which meet requirements in heavy loading districts. (The table for hard bare wire applies, generally, to transmission lines, and that for soft wire to distribution circuits.)

MINIMUM SAGS FOR HARD BARE COPPER WIRE AT 60° F. HEAVY LOADING DISTRICTS. GRADE "A."

Size, A.W.G.	Sag in inches for span in feet.					
	100	125	150	175	200	300
8	12	18	27	..	..	..
6	12	18	27	..	..	..
4	10	15	21	28	38	115
2	10	15	18	21	24	68
1	10	15	18	21	24	59
0	10	15	18	21	24	55
00	10	15	18	21	24	50
0000	10	15	18	21	24	42

WEATHERPROOF SOFT COPPER WIRE. GRADE "C."

6	21	32	48	..	..	..
4	18	27	40	..	..	..
2	15	22	33	45	60	..
1	12	18	27	37	48	..
0	12	18	26	35	45	..
00	12	18	25	33	42	..
0000	12	18	24	30	36	..

Clearances. — Minimum distances separating line conductors from the surface of the ground, from other electric supply lines, and from communication circuits, have been established in the National Electric Safety Code. In general, these are representative of good practice when space is limited. As far as is practicable, they should govern the design of overhead line structures, though greater clearances may, in some cases, be desirable.

Clearances above ground are established with a view to permitting normal traffic to pass under and along the line without interference or danger, and are as follows:

Nature of crossing.	Clearances in feet.		
	Lines under 300 volts. Guys, etc.	Lines 300 to 15,000 volts.	Lines 15,000 to 50,000 volts.
Over railroads	27	28	30
Over or along streets, alleys, traveled roads, or side tracks	18	20	22
Rural roads	15	18	20
Over walks or foot paths	15	15	17

Guys carried along a thoroughfare, but not crossing it, are not limited to 18 feet, but may be brought down to an anchor if local conditions permit.

On rural roads, where only pedestrians can travel under

the line, the clearance may be reduced to 12 feet for lines under 300 volts.

Clearance between wires of different systems, where not carried on joint poles at a wire crossing, are established as follows, the units being feet:

Wires crossing under.	Wires crossing over.				
	Up to 750 volts.		750 to 7500 volts	7500 to 50,000 volts	Guys, etc.
	Line.	Services.			
Communication......	2	2	4	6	2
Up to 750 volts......	2	2	2	4	2
750 to 7500 volts.....	2	4	2	4	4
7500 to 50,000 volts...	4	6	4	4	4
Trolley, railway.....	6	4	6	6	4
Guys, span wire, and services............	2	2	4	4	2

A clearance of 4 feet is required between supply wires up to 750 volts and communication wires, when the voltage to ground exceeds 300 volts.

The values in the table are based on span lengths of 100 to 150 feet. If the sum of the distance from the point of crossing to the two nearest points of support of the lines crossing exceeds 100 feet, these clearances must be increased 2 inches for each 10 feet of the excess up to 200 feet, and 2 inches for each 20 feet of the excess over 200 feet.

For voltages above 50,000, add .5 inch per 1000 volts to the above clearances.

The clearances required between the wires of a circuit at the points of support, are as follows:

Up to 750 volts..................................	6 inches
750 to 7500 volts................................	12 "
Over 7500 volts..................................	12 "

plus .4 inches per 1000 volts in excess of 7500 volts.

The minimum vertical separations required between wires carried on the same pole or other structure, but on different cross arms, are given in feet in the following table:

Wires at lower levels.	Wires at upper levels.			
	Up to 750 volts.	750 to 7500 volts.	7500 to 15,000 volts.	15,000 to 50,000 volts.
Communication wires	4	4	6	6
Supply wires up to 750 volts	2	2	4	4
750 to 7500 volts	..	2	4	4
7500 to 15,000 volts	..	..	2	4

These clearances are based on the assumption that men are permitted to work on the lower voltage circuit while the higher voltage circuit is alive. Clearances may be made 2 feet in some cases where men are not permitted to work on either circuit when the other is alive.

Clearance from Trees. — Where primary lines must be carried through trees, care must be taken to provide clearance from limbs as fully as possible. If the necessary permission can be gotten for judicious trimming it should be done. When the trees are very large it is usually preferable to carry the wires through the larger limbs below the main body of leaves. In this case insulators may be attached to the limbs or an abrasion molding to the wires to prevent wearing of the wire and burning of the limbs. Where trimming is not permissible to a sufficient extent to be effective, it is desirable to use tree wire having about $\frac{3}{32}$-inch rubber insulation covered with a layer of steel tape.

Arrangement of Wires. — The position of wires on the cross arms should be assigned according to a systematic plan. Circuits should be kept on the same side of the pole and in

the same pin spaces throughout their course, to facilitate location of trouble and to eliminate the possibility of accidents to workmen or property due to misunderstandings. In general, through lines and the highest voltages should be carried on the upper arms. Distributing mains and arc circuits supplying lamps in the vicinity should be carried near the bottom of the line. Secondaries should be carried on the lowest arm to facilitate service work.

The lowest voltages should be carried on the pole pins. Where side arms are used the primary wires should be carried at the outer end of the arm. The wires of a given circuit should be carried on adjacent pins and the neutral of low-tension or secondary wires should be carried in the middle. On four-wire three-phase lines the neutral should be carried at one side of the phase wires and, except on side arms, on one of the pole pins. With side arms it should be carried on the side of the circuit nearest the pole. In carrying connections across the pole for transformers or services, one side of the pole should be left free for climbing.

Joint Occupancy. — The use of a joint line of poles is preferable to separate lines on thoroughfares where there are many service drops. With lines on opposite sides of the street, the service drops of the lighting company must pass under or through the lines of the telephone company on the other side and vice versa. This introduces difficult situations which are eliminated when all drops are taken from one set of poles.

It is usually very undesirable to erect a separate line on the same side of the street with an existing line.

With alley lines the use of joint poles is the best method when the lighting line is carried high enough to permit all service wires to be carried above the telephone line.

Where poles are occupied jointly by electric light and tele-

phone or telegraph companies, the lighting wires should always occupy the upper part of the pole, as the telephone wires are more likely to break than the lighting wires. Fig. 129.

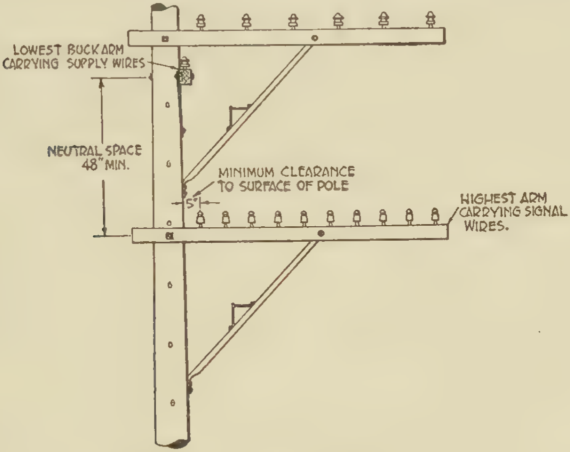


Fig. 129. Jointly Used Pole.

Transformer Installation. — Transformers are commonly supported on cross arms by iron hangers furnished by the manufacturers. A typical installation of a small unit is shown in Fig. 130. This class of construction is suitable for transformers of capacities up to 5 kw.

With single units of $7\frac{1}{2}$ to 15 kw. it is usual to use double arm construction for the arms on which the transformer hanger irons are carried. Units of 20 to 50 kw. are usually supported on a special 4 by 5 in. arm as shown in Fig. 131. Single units should always be hung in the middle of the cross arm and not at one side. Units of over 100 kw. are supported on a platform almost universally.

Where two or three transformers are mounted on the same pole, they must be so disposed as to give access to primary cutouts, and this is usually best accomplished by hanging the transformers on one side of the pole with the cutouts on

the back side of the double arm, as shown in Fig. 131. With the larger sizes, extra heavy bracing is desirable to take a part of the strain on the arms which support the weight.

It is not usual to support more than about three $37\frac{1}{2}$ kw.

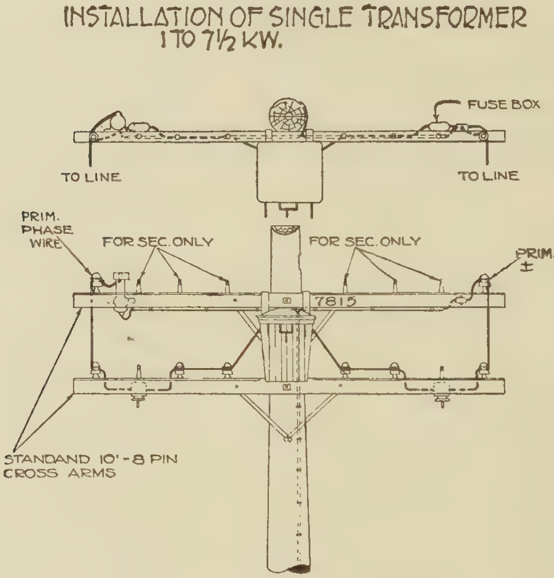


Fig. 130. Transformer Mounting.

transformers from a single pole. Two or more poles with a platform between is the preferable method of supporting the larger installations.

Such an installation, consisting of 75 kw. units, is illustrated in Fig. 132. The poles are reinforced at the butt by concrete to increase the stability against side strains. The weight is carried by two 4 by 10 in. timbers bolted to the poles, on which the platform is laid. The primary cutouts are all accessible from one side of the structure.

In large three-phase power installations, it is often desirable to be able to resume service with a minimum delay when

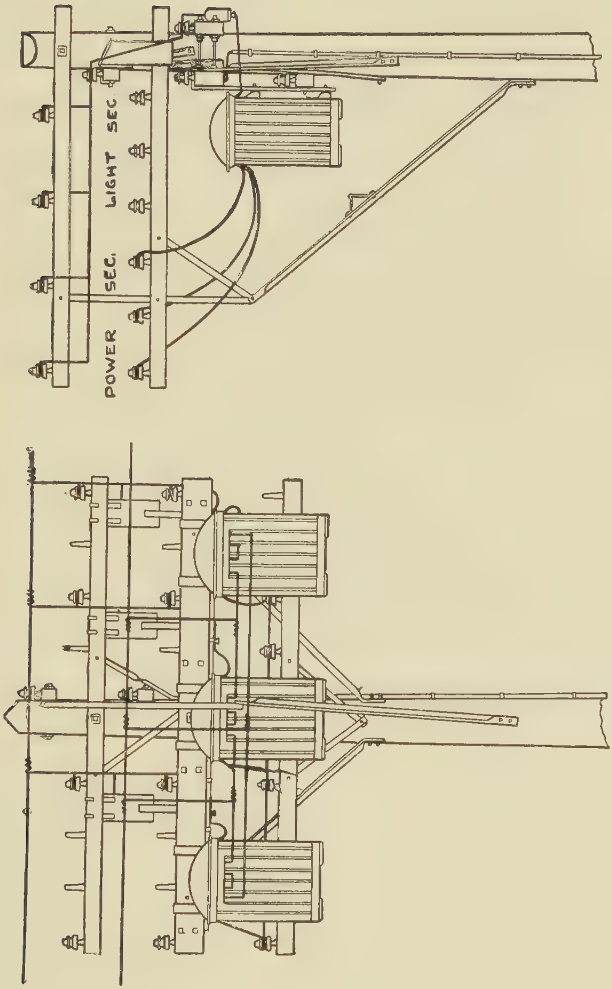


Fig. 131. Three-phase Transformer Installation.

one unit of a transformer installation fails. This is readily accomplished by providing suitable disconnectives in the secondary leads by which any defective unit can be quickly cut out. The primary may be disconnected at the fuse if

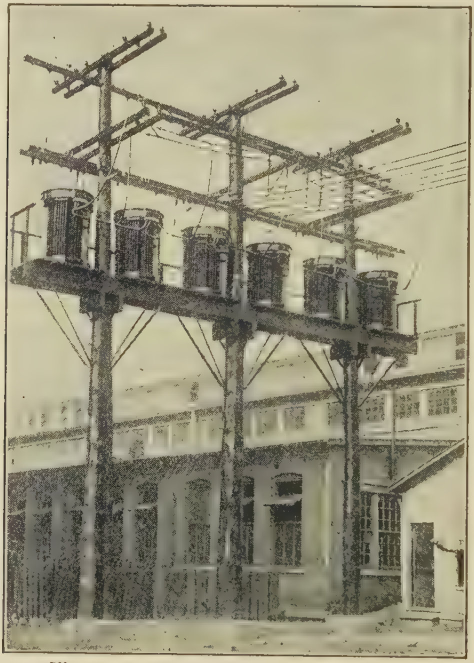


Fig. 132. Transformers on Platform.

there be such. If not, a disconnective single conductor porcelain pothead is found useful for the purpose.

Secondary Grounds. — To protect life and property in case a primary wire becomes crossed with a secondary at any point, it is very important that the secondary be grounded. This should be done by connecting to water pipes in customers' premises wherever these are accessible. The connection should be made on the line side of the service switch

so that it will not be disconnected at any time. Where the ground must be made outside the customer's premises, the most practicable method is to drive a galvanized iron pipe into the ground about eight feet, at the base of a pole near the transformer. If there are more than three spans of secondary

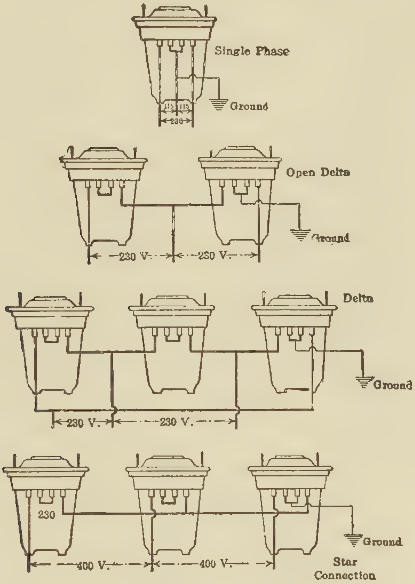


Fig. 133. Secondary Grounding Points.

main one ground should be installed for every 300 feet of secondary line.

The points to be grounded in various kinds of secondary mains are indicated in Fig. 133.

On a 220-volt single-phase power secondary the neutral point of the transformer winding should be grounded. With a two-phase four-wire power secondary, the mid point of each transformer winding should be grounded unless the motor windings served are interconnected so as to prevent it. In that event the neutral of one transformer

should be grounded. The same procedure should be followed with a three-wire two-phase secondary.

Fig. 134. Ground Wire Connector.

With a star-connected 200-volt or 400-volt three-phase secondary the neutral point of the system should be grounded, giving 115 or 230 volts to ground respectively from each phase wire.

With a delta-connected 220-volt system the ground connection should be made to the mid point of the winding of one transformer. This gives 110 volts to ground from each of the phase wires next to the ground wire and about 200 volts from the other phase to ground. There is some doubt as to the advisability of grounding a secondary when the difference of potential between any wire and ground will be higher than 250 volts, owing to the possibility that shocks from such a system may prove fatal under certain circumstances.

When connection is made to ground through a water pipe the wire should be attached by means of a copper clamp or other connection which may be securely attached to the pipe and wire.

When the connection is made to a pipe at the pole, the ground wire of # 4 or # 6 wire is preferably brought down the pole in a half-round wooden moulding, to protect the linemen and the public from accidental contact. The ground wire may be soldered to the pipe, or may be attached by means

of a pipe cap as shown in Fig. 134. This cap may be used to drive the ground pipe and at the same time produce a driven contact between wire and pipe. The pipe is usually driven down to the ground line with this cap in order to minimize the amount of exposed surface.

Rack Construction. — Secondary mains are carried on vertical steel racks in some situations, in the manner shown in Fig. 135. The advantages of this plan are that it saves a cross arm and gives a closer spacing between wires than is usual on cross arms, thus reducing inductive drop somewhat. The racks are used for supporting service drops, as well as live wires. An additional rack is placed on the opposite side of the pole to carry service going in that direction.

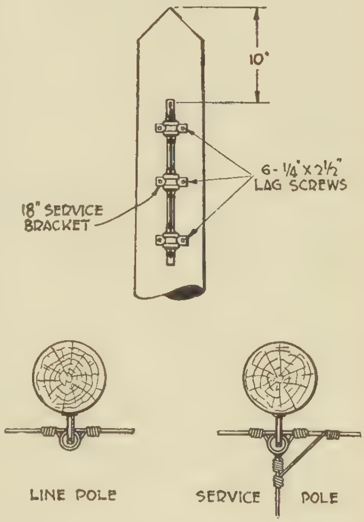


Fig. 135. Secondary Racks.

The disadvantages are that, where there are several service drops from each side of the pole, the climbing space is largely absorbed, and where pole space is limited, as in joint construction, vertical space is sometimes not available for rack construction. In districts where separate power secondaries are common, cross arm construction is necessary.

Rack construction, therefore, finds its best field of application in residence sections where line construction is simple and some improvement in appearance results from the absence of cross arms.

Service Connections. — Service drops should be tapped near the secondary line insulators and may be supported by them when they can be carried at such an angle from the pole that they will clear properly. Where they leave the pole at approximately right angles they may be supported from iron brackets or from insulators on a buck arm provided for the purpose. If there are several services taken from the

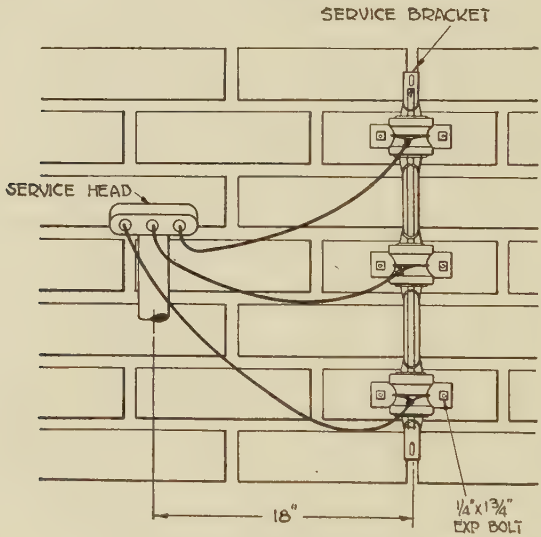


Fig. 136. Service Bracket.

same pole the use of a buck arm is the best method, as services can be taken to both sides of the thoroughfare in any desired number from one buck arm.

Where separate power and light services are maintained, the use of a six-pin buck arm provides facilities for both classes of service. The attachment of service wires to buildings is one of the most troublesome details of distribution work owing to the varying character of buildings, lengths of drops and angle of approach. Where three-wire service is

required, the necessity for reliable construction has led to the development of various forms of iron and steel brackets which are supported by expansion bolts when attached to brick or stone buildings.

The steel type of bracket, one form of which is shown in Fig. 136, is made also for support in a horizontal position. This bracket is used for sizes of wire up to # 0 B. &. S.

Street Lighting Construction. — Circuits for street lighting, when carried overhead, become a part of the general overhead system, and the line construction does not differ materially from that of other circuits, except at lamp poles, and, in some cases, on lamp loops.

Where the general system is in alleys, the lighting circuit must be carried to the adjacent street intersections, and a simplified construction is possible for such loops which carry only two wires. This is also the case, to a lesser degree, where lines are carried generally on streets.

Where lamps are mounted on poles carrying general distribution, as well as lighting circuits, the lamp loop is commonly brought below to a height of about 22 feet. This is often done by the use of duplex wire carried on insulator brackets around the ends of the line cross arms, or down the pole.

The lamp is mounted on some form of bracket on the pole, or suspended on a span wire diagonally across the intersection, with provision for lowering when renewals are needed.

Such circuits are sometimes carried on steel poles, where there are only a few wires on a residence street, and circuits are so operated that it is not necessary to work on them while they are alive.

In making a loop on series circuits an iron fixture having two pins and so arranged that it can be put in place of a line pin and known as a break arm is used.

CHAPTER XI

UNDERGROUND CONSTRUCTION

The use of underground construction has been general in the larger cities from the beginning of the electric lighting industry. Considerations of appearance and space prevented the use of overhead lines in the congested parts of the large cities where the early market for electricity was found. The greater first cost was found to have been well justified in the increased security to the service of important consumers to whom an interruption meant financial loss. The development of many of the large city systems proceeded at such a rate that in any event overhead construction would have become physically impracticable within a few years on account of the number and size of the feeders which were required to supply the network.

Edison Tube System. — The underground system devised by Edison was the earliest one to be commercially adopted, and much of this class of equipment is still in service, though other methods are now preferred. The Edison system remained standard for low-tension distribution for about fifteen years and was in many ways an admirable plan of low-tension distribution. It consisted of 20-foot lengths of iron pipe inside of which there were copper rods imbedded in a bituminous compound designed to exclude moisture and to insulate the opposite polarities from each other and the pipe. The rods were wound with a wrapping of jute, to prevent their sagging together, and were further held rigidly apart by separators at the ends. These 20-foot lengths were made

in various sizes of conductor from # 4 up to 500,000 c.m. for mains and up to 1,000,000 c.m. for feeders.

The Edison Company adopted what became known as the Edison wire gauge for their product. This gauge specified the number of thousands of circular mils in the conductor. The pipe with its conductor was called a tube, and a tube having conductors of 250,000 c.m. was called a 250 tube, or a tube with # 1 B. & S. conductor was called an 81 tube.

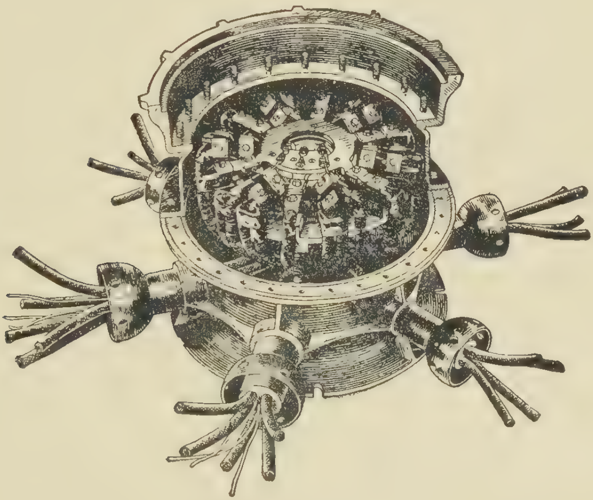


Fig. 137. Edison Tube Junction Box.

Such a gauge became necessary because most of the sizes of tubes were larger than the largest size of any existing standard wire gauge.

Sections of tube which were designed for use as distributing mains were made with three conductors of the same size, while those designed for feeders were made with one conductor about half the area of the others. This small conductor was used as the neutral, as the load on the feeder was nearly balanced and little capacity was required in the neutral.

Feeder tubes were also provided with three small wires which served as pressure wires to indicate the feeder end pressure at the station or substation.

The sections of tube were laid in the ground without other protection than would be given water or gas pipes. The copper rods were joined by means of soldered lugs with stranded flexible connectors. These connections were enclosed in cast-iron couplings, which were filled with hot compound after being bolted in place on the tubes. At intersections the tubes were interconnected through junction boxes, which carried the necessary fuse clips and nuts by which a main was automatically disconnected in case of breakdown, or could be opened by repair men for testing purposes. These boxes were made so that 4, 6, 8 or 10 tubes could be brought together in one box, as was necessary at the intersection of two streets where a feeder was tied in, and where there were lines going each way on both sides of the street.

Tube lines were carried along each side of the street near the curb to facilitate the introduction of services into consumers' premises. A single line was run where the consumers were scattered and where the alleys were used. Service connections were made by a T-connection applied at any joint in the line. The service tube was carried through the building wall into the sidewalk area or into the basement of the building. Where the buildings were not built out to the property line, the service was extended underground across the consumers' premises or brought up on a pole at the lot line and carried thence overhead to the building. The expense of the line across the private property was usually borne by the consumer, and the decision as to the method of installation commonly rested with him in such cases.

The Edison tube system was the standard method of distributing low-tension current underground until about the

year 1897, when cables drawn into ducts began to be employed for the heavy feeders. This change was made on account of

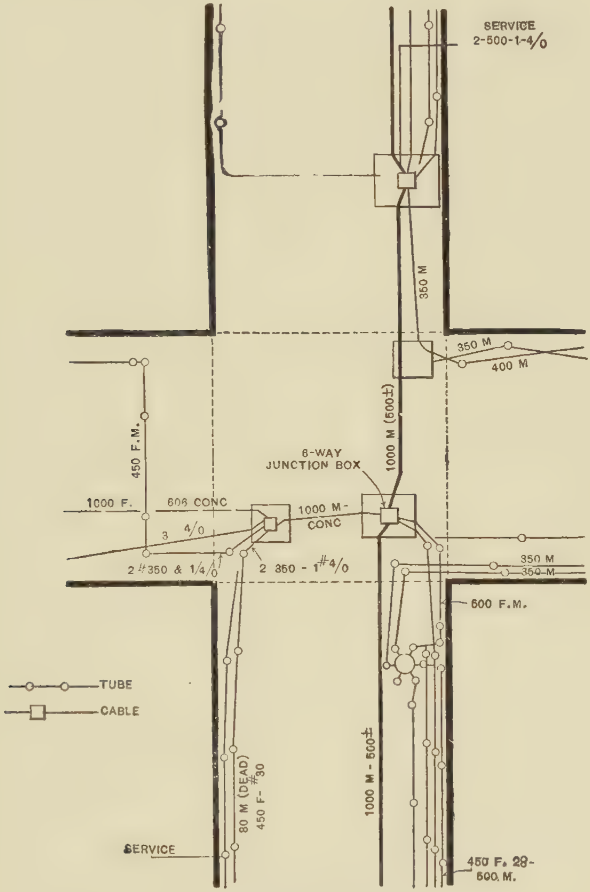


Fig. 138. Edison Tube and Cable System.

the inability of the tube feeders to carry overloads without melting the compound in the joints and causing burn-outs. With cable it was found that the copper could be run with

heavier loads and therefore more economically from an investment standpoint.

Furthermore the necessity of opening street pavements in each case where repairs were made involved considerable expense, as several openings were usually made before the trouble could be definitely located.

The feeder system and the heavier distributing mains were therefore gradually worked over to a " draw-in " cable system as rapidly as reinforcement was needed from year to year. The systems as they exist, therefore, embody a combination of cable and tube work such as is shown in Fig. 138, which illustrates the feeders and mains at an important street intersection in Chicago.

Conduit Systems. — The early alternating and series arc systems which were installed in situations requiring underground constructions were unable to use a system similar to the Edison tubes because of the higher voltages employed. The engineers were therefore compelled to seek other means of installing their conductors. A variety of materials was tried, but the method was that of a draw-in conduit system with manholes for handling the cables in nearly every case. One of the earliest was the Dorset system, which consisted of sections of multiple duct made up of an asphaltic concrete joined together by pouring hot compound around the joints. These joints failed to remain in alignment and the asphalt ducts became distorted, so that the work of installing cable became difficult if not impossible.

Creosoted wooden pump log was tried because of its ease of jointing and low cost. It was not satisfactory for power cables, the creosote with which it was impregnated being inflammable.

Other systems were developed in which the ducts were intended to provide insulation for the conductors, but expe-

rience proved that it was not at all practical to maintain such a system, and all such attempts were abandoned.

The efforts of engineers were then directed to systems in which the construction was more nearly fireproof, of greater durability, and yet economical to construct and maintain.

This naturally led to the development of methods in which the insulation was applied to the conductor and the conduit was of some fireproof material which would be durable underground.

Among the earlier forms of duct of this sort was one which consisted of sheet-iron tubes lined with cement. It was made in 4-foot lengths, with ferrules at the ends to preserve the alignment, and when properly laid obviated many of the difficulties experienced with the earlier forms of duct. A considerable amount of it was installed in some of the larger cities. Where it has been subjected to cable burn-outs with large power behind, it has been found, however, that the cement does not hold up under the heat of an arc, and that the metal sheathing is apt to assist in the spread of the short-circuit. The use of this form of conduit has, therefore, not been continued.

While these various forms of duct were being tried out, other engineers were introducing ducts of terra cotta and clay tile, these materials being fireproof and of indefinitely long life. Multiple and single duct was tried and the alignment and security from outside interference were gotten by protecting the ducts by concrete or creosoted plank. This class of construction is the most generally used where a draw-in system is employed.

A substitute for clay tile was developed in later years consisting of a concrete duct, known as " stone conduit." This is made by pouring a suitable mixture of sand and cement into molds about three feet long where they are left until sufficiently set to bear handling. They are seasoned and fitted

with sheet iron ferrules which are centered carefully with the inside of the duct, so that alignment will be assured when laid. The 3-foot lengths are laid with joints staggered in a surrounding jacket of concrete, thus making a solid line of concrete which is very durable.

In the effort to get an insulating conduit, the use of paper or fibrous tubes impregnated with moisture repellent compounds was tried. The earlier forms of this type of duct were not strong enough mechanically to prevent collapse under continuous exposure to moisture. In later years, however, processes of manufacture were developed which produced a waterproof form of fiber duct, having ample mechanical strength when surrounded by concrete, and not readily inflammable. This type of duct is made in lengths of about five feet, is easily handled because of its light weight, and when laid with concrete between adjacent ducts makes a quite durable structure. It has advantages for cross country lines where transportation and breakage of tile duct are expensive, for telephone and similar systems where no fire hazard is present, and has been used for light and power distribution to some extent.

Built-in Systems. — In Europe underground lines are often laid in the ground without provision for additions or removals except by making further excavations. Such systems may be termed " built-in " as distinguishing them from the " draw-in " systems common in America.

Built-in systems have not been used generally in America since additions to the Edison tube systems were discontinued in favor of draw-in conduit systems.

The rapid growth of electric service systems in American cities made the draw-in system more economical and expeditious.

In European cities the Edison tube system was displaced

by laying armored cables in spaces under sidewalks or in parkways, with provisions for service tape from small surface boxes at suitable intervals.

Transmission cables are also laid along highways in a similar manner, the joints being covered with an enclosure which is suitably marked on the surface.

Another method consists of laying earthenware ducts open on top in which the cables are laid and the line then covered with a protective slab or planking.

In some cases low voltage lines are covered with a hot bituminous compound after laying.

Location of Duct Lines. — In the location of a duct line the presence of other piping systems, duct systems, sewer manholes and the like must be taken into account. It is desirable to select the side of the street which is least obstructed by such obstacles. The municipal records should be consulted to get the location of the water piping and sewer systems, if such records are available. Other duct systems may be located by the manhole covers which appear on the surface.

In crowded streets and where records are not available, time is saved by excavating a test trench across the street at several points for the purpose of locating the piping and other systems which cannot be identified from the surface.

Laying out a Conduit Line. — In the design of a draw-in duct system, the number of ducts, the size of manholes and their location are the important considerations.

The *number of ducts* must be fixed by the requirements of the route to be followed. There must be sufficient to care for the local distribution, for distributing feeders, for transmission lines and for future requirements. The distributing mains for a low-tension system usually fill one duct, but with

alternating mains and underground secondaries two ducts must be reserved in many parts of the system. The feeder and transmission line requirements are fixed by the proximity to stations. The reservation of duct space for future requirements is very important if the system is a growing one, as the expense of adding a few ducts at a later date is much larger than if they are laid when the trench is open. It is therefore desirable to lay sufficient ducts in advance to care for probable requirements for at least five years ahead. It is not advisable to lay less than four ducts in a line except on side streets where there is no probability that the line will ever become part of a through line. In such cases two duct lines are installed.

The maximum size of duct lines is limited by the radiation of heat from the cables and by the space available in manholes for proper training and the accessibility of cables.

With ducts laid four wide two cables are trained around each side of the manhole and the cable next to the wall is accessible for repairs or alterations. With more than two cables on a rack the back cables cannot be readily reached for such work.

The radiation of heat from cables in a duct line more than four wide is so retarded as to seriously reduce the current capacity of the cables in the inner ducts.

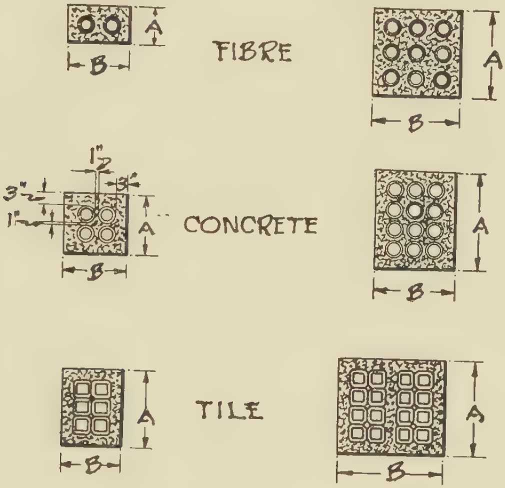
Under these limitations it is the practice in many cases to limit duct lines near a station to 16 ducts laid four wide and four deep, and to reduce the lines to 12 ducts as near to the station as the local arrangement of branch lines will permit.

The cost per duct foot is not sufficiently reduced in lines having more than 16 ducts to make the larger duct lines especially advantageous from the point of view of first cost.

The arrangement of ducts should be as near square as the number of ducts will permit. When the arrangement is

rectangular, the amount of excavation is usually less if the horizontal dimension is the narrower one.

The usual arrangement of various numbers of ducts up to 16 are seen in Fig. 139. With 12, 16 or 20 duct lines it is preferable not to exceed 4 ducts wide in order to avoid un-



DIMENSIONS FOR 3½" DUCT							
NO OF DUCTS		2	4	6	9	12	16
FIBRE	A	10	16	16	22	28	28
	B	16	16	22	22	22	29
CONCRETE	A	11.0	16.5	16.5	22	28	28
	B	16.5	16.5	22	22	22	30
TILE	A	11	16	16	21	26	26
	B	16	16	21	21	21	29

Fig. 139. Duct Sections.

desirable conditions in manholes. With 16 ducts arranged as in Fig. 139, a double row of cables may be trained around each side of the manhole, making all cables accessible for subsequent changes in connections or for repairs.

In large systems where the energy available in case of a cable burn-out is sufficient to do considerable damage to the conduit system, it is desirable to separate the two middle vertical rows of lines having 12 or more ducts by filling the space with about three inches of concrete. This limits the damage to cables to one-half of the line, if the burn-out occurs

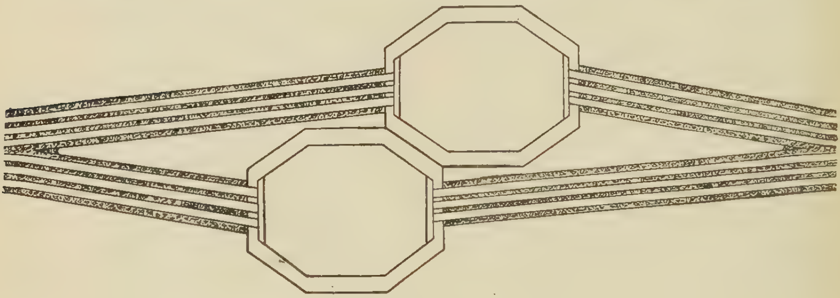


Fig. 140. Divided Manhole.

outside of a manhole. Trouble in manholes may be segregated in a similar manner by a divided manhole as shown in Fig. 140.

This construction is advisable in manholes near generating stations, where there are many cables and the severity of a burn-out is great because of the proximity to the source of supply.

Laying Out Curves. — While conduit lines should be laid out in straight lines as far as is practicable, there are occasional situations where the line must be given an offset to pass an obstruction or must curve to reach the terminus of the line.

Such curves may be employed within proper limits without requiring an excessive tension for drawing in the cable.

The following table shows the maximum deviation in feet which can be used for different lengths of pull between manholes. The designation " single curve " refers to a deviation

which occurs only at either end of a section. A reverse curve is an offset which curves to one side and then swings into a line parallel to but one side of the original line. A double reverse curve is an offset to one side which is brought back into the original line projected forward.

The columns *A*, *B*, *C*, and *D* show maximum offsets for cables of different sizes.

Column *A* is for cables having a diameter of not over 60 per cent of the inside diameter of the duct.

Columns *B*, *C*, and *D* are for cables having a diameter of 61 to 70, 71 to 80, and 81 to 90 per cent respectively of the diameter of the duct.

The figures in these tables are based upon tests made in Chicago and are designed to limit the stress on any cable to approximately one-third the sum of the ultimate tensile strengths of the copper conductors.

Length of pull.	Maximum offset in feet.											
	Single curve.				Reverse curve.				Double curve.			
	A	*B*	*C*	*D*	*A*	*B*	*C*	*D*	*A*	*B*	*C*	*D*
100	34	34	34	17	14	14	14	9	10	10	8	2.5
200	34	32	20	3	14	14	11	2	6.5	5.5	3	1
300	26	21	9	1	13	12	5	..	4	3	1	..
400	16	13	5	..	9	6.5	2	..	2	1.5	..	..
500	10	8	1	..	5.5	4	..	..	1	..	..	..
600	6	4.5	..	..	3	2	..	..	..	..	..	..
700	3.5	2.5	..	..	1.5	1	..	..	..	..	..	..

In laying curves, the maximum offset of the individual pieces of duct should not exceed 1.5 inches for pieces 18 inches long or 3 inches for pieces 3 feet long.

Location of Manholes. — The use of a draw-in system involves the construction of vaults called manholes at all points

where the cable must be jointed and where lines turn or intersect.

Where long runs occur without intersecting other lines, manholes must be provided with sufficient frequency to permit the drawing in of cable without damage to the cable insulation. This usually requires that they be not over 500 feet apart, and with large cables which nearly fill the duct 400 feet is a safer limit.

The location of manholes on a length of line which is not intersected by other duct lines at each block should be made as far as possible with a view to their being used as intersection points later. That is, they should be located so that any conduit line built on an intersecting street later may be connected with existing manholes. It is impossible to predict with certainty which side of an intersecting street will be used, but the location of manholes at street and alley intersections will minimize the necessity for duplication. Where distribution by overhead lines in alleys with underground lines on the street is used, manholes should be put opposite alley intersections where it is practicable to do so.

The number of manholes required in blocks where numerous underground service connections are required is dependent somewhat upon local conditions, but must usually be sufficient to permit service pipes to be brought into sub-sidewalk areas or basements at intervals as required. In the denser portions of the system this results in the location of small manholes at intervals of 75 to 125 feet, while in other parts they may be 150 to 200 feet or more apart. In distribution by means of underground transformers and a secondary network, it is necessary to build extra large manholes for the transformers in order to get sufficient room and proper ventilation.

Construction of Manholes. — The shape of manholes is made to suit local conditions, to clear obstructions and to

bring the ducts in from the different directions as required.

In general, however, there are several types which may be used where no local obstruction interferes and these are shown in outline in Fig. 141.

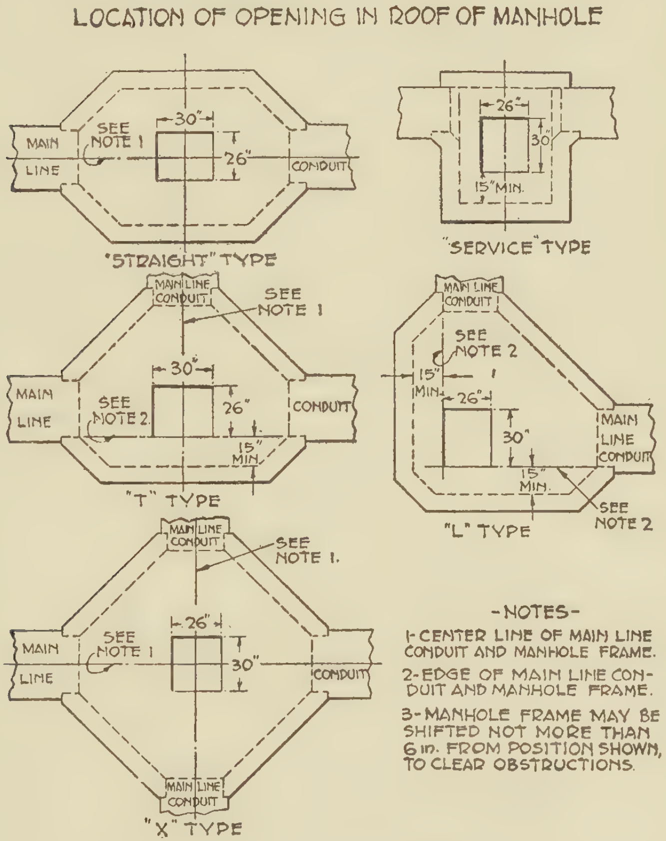


Fig. 141. Types of Manhole.

The "straight" type is used in lines at points where no intersection occurs.

The T-type provides for a line at right angles in one di-

rection only, while the L-type makes a right angle turn in a single line.

The X-type provides for a crossing or intersection and is the most common type in city distribution.

The " service " type is a small hole which allows the ducts to pass through one side without exposing any of the cables except those used for local service.

The openings are so placed as to intersect the center line of each duct system entering the hole, thus permitting cable to be readily drawn in or out in any direction. The space required for cables is fixed by the number of ducts coming into the manhole, and this must be sufficient to allow of training these cables safely and with a reasonable degree of accessibility for repairs or changes. The probable installation of junction boxes must be taken into account also. In practice it is usual to provide manholes 5 feet by 5 feet at junctions where there are eight ducts, that is, where two 4-duct lines cross, 6 feet by 6 feet where there are 12 to 18 ducts, 7 feet by 7 feet where there are 20 or more, and larger as the needs of the case may require.

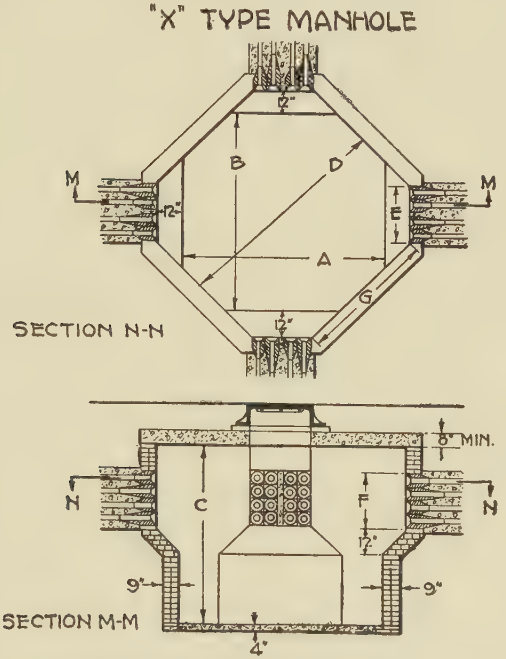
The size and shape of manholes in congested districts are often governed by local obstructions such as gas or water mains and services or the conduit lines of other public service companies. Manholes must frequently be built so as to include a gas or water main, and the size must be increased to get the necessary space.

The introduction of cables operating at voltages above 15,000 necessitates more length in manholes for joints than is required for lower voltage cables. The joints for 33-kv. cable are over twice as long as for 13-kv. cable.

For voltages above 33 kv., the joints are of such length that manholes must be specially designed to receive them and old manholes must be rebuilt if the line is to be carried in existing ducts.

One method of adding the necessary lengths to the cable training space with a minimum amount of additional excavation and brick work is shown in Fig. 142.

The depth of manholes must be sufficient to give head room and yet should preferably not be so great as to carry the



SIZE OF MANHOLE	NO. OF DUCTS		A	B	C	D	E	F		G
	(1)	(2)						(1)	(2)	
6 FT. X 6 FT.	2	4	6'-0"	6'-0"	6'-0"	5'-9"	14"	7"	14"	5'-2"
7 FT. X 7 FT.	6	9	7'-0"	7'-0"	7'-0"	7'-8"	21"	14"	21"	5'-2"
8 FT. X 8 FT.	12	16	8'-0"	8'-0"	8'-0"	8'-10"	2'-4"	21"	2'-4"	5'-4"

Fig. 142. Extended Type Manhole.

floor of the manhole below the sewer level. Small distribution manholes which are used only for service connections may be more shallow than larger holes where work is done frequently. Service manholes may be 5 feet inside, while

junction manholes should be 6 or 7 feet from roof to floor. In some cases a shallow form of manhole known as a handhole is used for distribution laterals. These are made about 3 by 4 and 3 feet deep. They are placed above the conduit line, so that only the top row of ducts enters the handhole. The distributing mains are thus accessible for service taps and the through lines in the lower ducts are not in the way. Service laterals are usually laid just under the paving, so that they enter the handhole at a convenient level. Handholes should have covers large enough to afford access to the distributing main.

Manhole walls are usually of brick, and the floor and roof are of concrete. Concrete walls poured to standard forms are sometimes used in outlying sections where no other underground pipes or structure interferes with the placing of forms. In the central parts of cities, the manhole is frequently built around one or more obstructing structures and the walls are laid up in brick as the most expedient method.

The type of brick known as "sewer" brick should be used for manhole walls, and a good sand and cement mortar is necessary for permanence and strength. The walls are usually made 9 inches thick, but for depths greater than 9 feet, a 13-inch wall is usually required.

The floor is poured after completing the sewer connections and laying up the side walls. A depth of 3 inches of concrete is usually provided. In some localities where a sandy soil, of such elevation that it drains naturally, exists, no water accumulates and no sewer connection or floor is required.

The manhole roof must have sufficient strength to support the street traffic passing over it. In traveled streets this requires the use of steel reinforced concrete of ample strength, such as that shown in Fig. 143. The concrete is poured to a depth of 8 inches and is reinforced by steel bars of one

inch square, placed in a manner similar to that shown for a T-manhole in Fig. 143.

In another type of roof the steel consists of used rails or T-iron, laid with such spacing that brick can be used to close

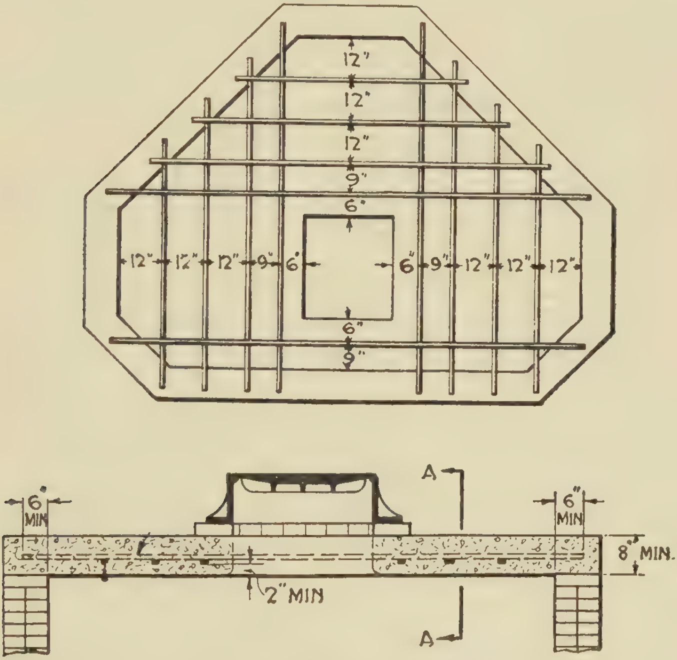


Fig. 143. Manhole Roof Construction.

the space between. This type requires a greater weight of steel and usually costs more than a concrete roof, reinforced.

The roof of the manhole is so graded that the paving may be placed above it.

Manhole covers are of cast iron, the frame being set on brick to adjust it to the proper level with the surface of the paving.

The removable cover is 26 to 30 inches in diameter if circular and about 26 to 30 if rectangular.

Manhole covers are usually of the ventilated type, this type affording opportunity for escape of gas from the manhole to a considerable extent.

It also permits some circulation of air in duct runs which, at times, becomes heated to temperatures above that of the outside air.

The quantities of material and amount of excavation and paving required for manholes of the various standard types are set forth in the following table.

QUANTITIES REQUIRED IN MANHOLE CONSTRUCTION

Type.	Straight.			"L"			"T"			"X"		
Size, feet	4×5	5×6	6×7	5×5	6×6	7×7	5×5	5×6	6×7	6×6	7×7	8×8
Excavation, cu. yds.	10	15.2	21.2	12	16.5	24	14	19	25	19	25.5	33.3
Sand, cu. yds.	1.7	2.2	2.9	2.6	3.3	4.2	2.7	3.25	4.2	3.2	3.8	4.6
Stone, cu. yds.	1	1.33	1.75	1.5	1.9	2.5	1.5	1.9	2.4	1.5	1.9	2.5
Brick, thousands	1.4	1.8	2.35	1.7	2.18	2.73	1.75	2.15	2.65	2.25	3.65	3.13
Cement, bags	19	24	32	24	32	40	25	31	39	33	37	45
Paving, sq. yds.	6.2	8	10	7.1	9	11.1	6.5	8	10	9	11	13.5

Types of Duct. — Duct material is of vitrified clay tile, concrete pipe or impregnated fiber.

Tile duct is made in single- or multiple-duct. The multiple-duct is, however, not used generally for power cables, though it has advantages for telephone and similar work.

Single-duct is used in the larger power systems to secure the double thickness of material between adjacent ducts and this is usually supplemented by an inch or more of concrete between ducts.

Tests made with large generating capacity have shown that the heat of the arc resulting from a short-circuit in one duct will break down the duct wall and damage the cable in the ad-

jacent ducts in a few seconds when there is only the thickness of the duct material between the cables.

Single concrete ducts laid with one inch of grouting between have been found to amply protect cables in adjacent ducts against arcs which are cut off within a few seconds.

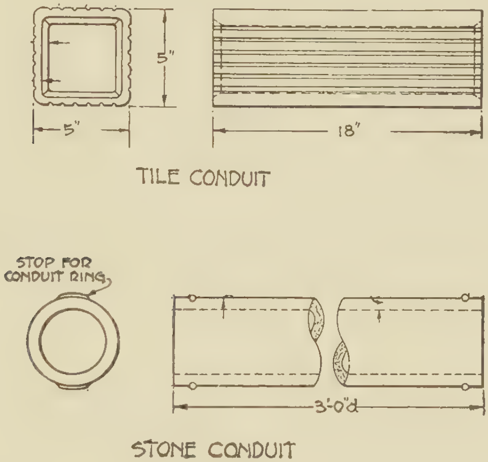


Fig. 144. Types of Duct.

Fiber ducts are usually laid with two inches of concrete between them to secure the required protection.

The tile duct is usually made in 18 inch lengths while concrete and fiber ducts are made in 3 to 4 foot lengths.

Fiber duct has the advantage over other forms of duct that it is lighter in weight and less subject to loss by breakage in handling.

Laying Conduit Lines. — In paved streets conduit must be laid at such a depth that the top of the conduit will be below the concrete foundation of the pavement with enough soil between to provide a cushion for the heavy traffic on the pavement. This usually brings the top of the conduit run

not less than 2.5 feet below the surface. This is sufficient, also, to bring the conduit into manholes at a convenient level in the average situation.

In crossing under a railroad the depth should be about 3.5 feet from the top of the rail to the top of the duct structure and the concrete jacket should be increased to 5 or 6 inches in thickness in sections laid under tracks.

The grade of a section of line should be made highest about midway between manholes with a slope each way of about 1 inch per 100 feet, to give drainage. It is important that low spots be avoided, as the freezing of water in a duct section is likely to damage both cable insulation and the duct structure.

Where paving is removed the width of the opening should not be more than is necessary to permit installation of the conduit line.

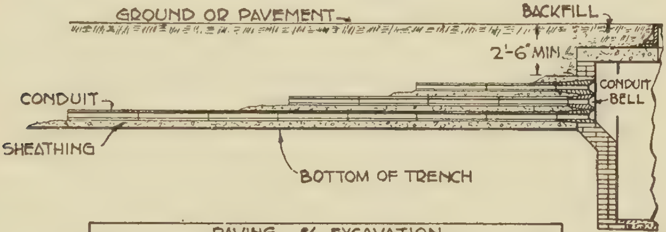
The conduit line must be protected, when laid in public thoroughfares, from future excavators. It should also be made secure against the possibility of getting out of alignment and thus injuring the cable or making it impossible to pull cable in or out. In view of these considerations it is usual to surround important lines with concrete on all sides to a thickness of three inches. This makes an envelope thick enough to support short sections around which excavations may be made later and also protects the tile from the laborer's pick. The concrete when set acts as a watershed to a large extent and minimizes the entrance of leaking gas into the conduit system.

In laying the duct the bottom of the ditch is leveled at the proper grade, and a layer of three inches of concrete is spread and tamped on the bottom. The lower layer of ducts is placed with the proper horizontal spacing, the joints between duct sections being staggered so that they are separated at least six inches. The ducts are then covered with concrete

to the necessary depth (1 or 2 inches). Another row of ducts is then laid and the process repeated until the top is reached, when a layer of three inches of concrete completes the jacket.

The work progresses in practice in the manner shown in Fig. 145, the complete line being built up as the length is increased.

In clay soil it is often possible to make the width of the trench the same as the outer dimensions of the duct line, thus



PAVING & EXCAVATION (PER TRENCH FOOT)							
NO. OF DUCTS		2	4	6	9	12	16
PAVING	SQ.YDS.	.33	.33	.39	.39	45	45
* EXCAVATION	CU.YDS.	.051	.082	.115	.160	.205	.271
LIST OF MATERIAL (PER TRENCH FOOT)							
STONE COND.	FT.	2	4	6	9	12	16
CEMENT	BAGS	.18	.25	.32	.39	43	.61
STONE	CU.YDS.	.034	.044	.054	.063	.072	.096
SCREENINGS	CU.YDS.	.004	.012	.018	.027	.036	.048
⊙ SAND	CU.YDS.	.02	.028	.03	.036	.036	.048

Fig. 145. Conduit Construction.

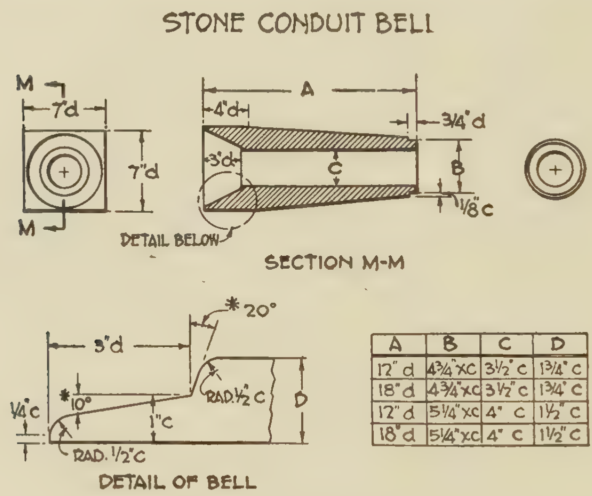
using the side wall as a form for the jacket and saving the use of lumber.

It is important that the joints between duct sections be as close fitting as practical to prevent leakage of wet concrete into the interior of the ducts. Such leakage when set may endanger the lead sheath of cables when drawn in later.

Concrete duct is protected when laid by a sheet iron collar placed over the joint and drawn snugly around the outside

of the duct. Muslin or other similar material has been used for this purpose.

At the point where the ducts enter the manholes the end of the duct is often provided with a flaring concrete bell such as that shown in Fig. 146 which permits the installation of cables of larger diameters with an easier radius of bend and eliminates



A	B	C	D
12" d	4 3/4"xC	3 1/2" C	1 3/4" C
18" d	4 3/4"xC	3 1/2" C	1 3/4" C
12" d	5 1/4"xC	4" C	1 1/2" C
18" d	5 1/4"xC	4" C	1 1/2" C

Fig. 146. Conduit End Bell.

a sharp corner which may chafe the lead sheath with the movement incident to expansion and contraction under temperature variations.

With lines built in parks or on roadsides it is sometimes sufficient to lay the ducts on two-inch creosoted plank with a similar plank over the top of the ducts. Such construction is less expensive in first cost, and if not disturbed is quite durable.

Where the space for installation of conduit is limited as in crossing under street railway tracks, water pipes, etc., the change in grade may be minimized by making a short

section of line with a flat formation, one or two layers high. In such cases it is often simpler to use wrought iron pipe without concrete for the section of ducts where the crossing occurs. A manhole is built each side of the crossing.

Pole Connections. — Where connections are made to overhead lines as is customary with alley line distribution supplied from conduit lines on streets the " lateral " connection is made from a manhole to and up the pole.

The portion of the branch between the manhole and the pole may be of iron pipe or conduit.

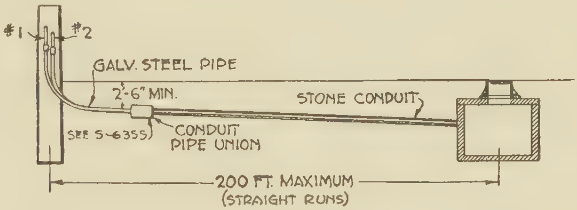


Fig. 147. Lateral to Pole.

Iron pipe is used from the base of the pole to the cross arm where the cable is terminated and galvanized pipe is found most durable for this purpose.

Where the manhole is within 20 feet of the base of the pole, the pipe is usually extended to the manhole. If the distance is greater the added cost of the iron pipe makes it preferable to use a two-duct conduit line from the base of the pole to the manhole. The usual arrangement with concrete conduit and pipes is seen in Fig. 147.

Service Connections. — The arrangement of service laterals or subsidiary connections from the main duct line to consumers' premises is a matter of much importance, as it forms a large part of the underground investment in congested districts. Local conditions often fix the character of the de-

sign, so that no universal method can be laid down. In some cities a separate service lateral is not required for each building into which service is to be introduced and the laterals may be placed at intervals of 75 to 100 feet or more, the intermediate buildings being connected by means of interior wiring through sub-sidewalk areas or building basements. This method is much less expensive than that required in cities where each building must have its own service connection, as it requires fewer distributing handholes or

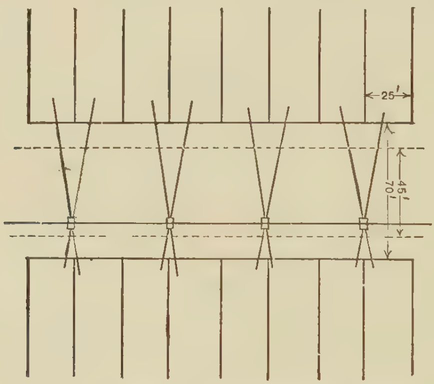


Fig. 148. Service Handholes and Laterals.

manholes and a much less mileage of lateral pipe and service cable.

Where service laterals can be spaced 100 feet or more apart a single duct line is sufficient to care for the service on both sides of the street. Lateral connections are run to each curb or building line from the service manholes. With a street more than 100 feet wide, it may be more convenient to use two duct lines to save the long laterals. In very congested districts it is advisable in this class of construction to put in double laterals each way to facilitate repairs or changes in the cable work or to give emergency service to important consumers.

Where separate service is required for each building, this plan may result in the installation of manholes or handholes at intervals of 50 feet as in Fig. 148, where buildings are on 25-foot lots and service is required in nearly every building. In such cases it is less expensive in the long run to establish service handholes at intervals of about 100 feet on each side of the street. The arrangement shown in Fig. 149 is worked

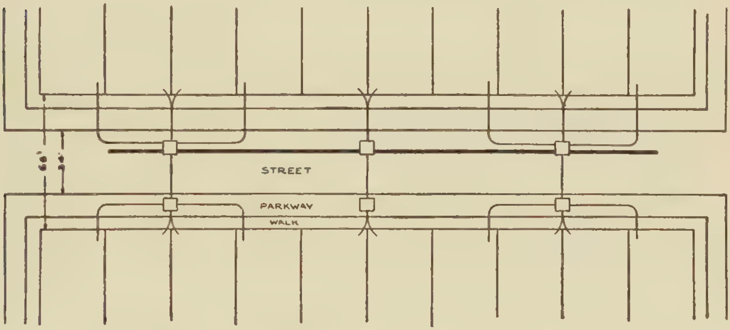


FIG. 149. Double Handholes for Service Connections.

out for a street 66 feet wide, with 34 feet between curb lines. This arrangement requires less lateral cable and pipe and is the most feasible arrangement in streets where there are car tracks under which laterals must be carried. The advantage of the construction shown in Fig. 149 increases with the width of the street. It is also an advantageous plan where there is a parkway in which the laterals can be laid, no paving being disturbed except at the street intersections.

CHAPTER XII

UNDERGROUND CABLES

Types of Cable. — Cables used for the underground distribution of electricity consist of a conductor or group of conductors insulated suitably for the voltage at which they are to be operated and enclosed in a lead sheath for protection from moisture. If the cable is to be laid without the protection of a conduit system, it may be further protected from mechanical injury by an armor of steel tape or wire. It is then known as an armored cable. Cables having but one conductor are known as single-conductor cables, those having two conductors are known as duplex or twin and those having three conductors as triplex or three-conductor cables.

Duplex and triplex cables are those in which the conductors are spirally arranged in the lead sheath, the voids being filled to make cable of circular cross-section as in Fig. 150. Twin cable is that in which the two conductors are arranged in one plane without twisting or filling in the voids with jute.

Two-conductor and three-conductor cables are also made with a concentric arrangement. After the central core is insulated for the intended voltage, the strands of the next conductor are spirally wound around it and the insulation is applied in the usual manner.

If it is to be a two-conductor concentric cable, the lead sheath is then applied. If not, another layer of copper and insulation is added, making it a three-conductor cable before the lead is applied.

Where it is necessary to get the maximum cross-section of

copper within a given diameter of lead sheath, the copper conductors are formed so as to make a cross-section shaped like a sector of a circle. This permits the use of more copper in a given space as the copper occupies a part of the space which is occupied by fillers.

Cables having as many as 10 or 12 conductors of #6 or #8 A.W.G. have been used to some extent for series light-

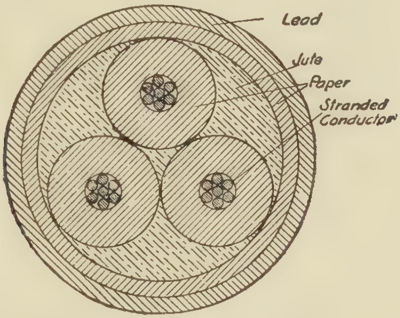


Fig. 150. Three Conductor Cable Section.

ing circuits, where all the circuits were carried underground through a district without loops.

In large systems, the great number of feeder and transmission cables makes it desirable that the standard size of feeder cables be as large as practicable. In systems working at pressures up to 13,200 volts, the practical limit is often found in the fact that a $3\frac{1}{2}$ inch duct size was adopted in the earlier years of development. With three-conductor cables, such as that shown in Fig. 150, this fixes the maximum size of a paper cable at about 500,000 c.m.

By the use of a sector type of conductor it is possible to increase the copper section to about 650,000 c.m. at 13,200 volts. Such a cable is shown in Fig. 151. This type of cable has a further advantage in current carrying capacity, because of the greater arc of contact between conductor and sheath,

and this favors its use even where the duct size is not a limiting condition.

Use of Various Types of Cable. — The use of multiple-conductor cables is generally advantageous because of the saving in the cost of the lead sheath as compared with an

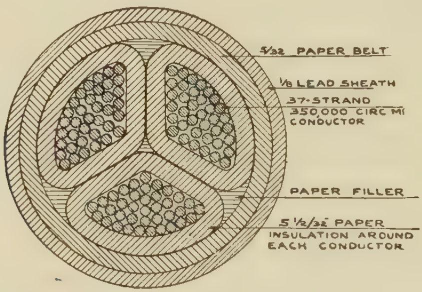


Fig. 151. Cross-section of 13,200-volt, 350,000-c.m. Sector Cable.

equal number of similar single-conductor cables. However, there are certain disadvantages incidental to taps and joints which tend to offset some of the advantages. Practice therefore varies according to the use to which the cable is put.

In general, single-conductor cable is used when frequent taps are required, as in distributing mains, while concentric and other multiple-conductor cables are used for through lines where taps are not made. Twin cable has been used quite extensively in series systems, and in single-phase taps of alternating-current systems. It is difficult to train in manholes, as it does not bend easily in the plane of the conductors, and with paper insulation is susceptible to injury from bending at too small a radius.

Concentric cables are used in preference to duplex where the conductors are over #0.

The sector type, two-conductor cable, in which each conductor is "D" shaped or semi-circular, has found convenient application for low-tension feeders.

This cable, shown in Fig. 152, is found somewhat easier to joint and has better current carrying capacity than the equivalent size of concentric cable, because each conductor has opportunity for direct radiation of heat through the sheath.

Low-tension distributing mains on direct-current systems are usually of single-conductor cable to facilitate making service taps with the cable alive. Such taps are usually

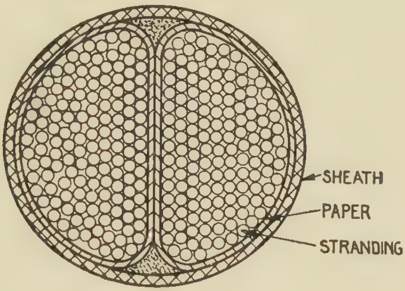


Fig. 152. "D" Type Cable.

numerous, and nothing is gained by the use of three-conductor cable for such mains.

With alternating-current low-tension mains of over 250,000 c.m., three-conductor cable is commonly used as a means of avoiding the flow of induced currents through the sheaths of adjoining cables, as is likely to take place when single-conductor cables are used.

Where this is done, the service taps are taken off through a service box, or by splicing in pieces of single-conductor cable, from which the taps are taken.

The service cables, being short, are usually more conveniently handled if made single-conductor.

Two-phase and three-phase feeder and transmission cables are preferably of three or four-conductor cable, as the case may require. This practice, besides saving in the first cost

of cable, permits the use of a single duct for larger sizes of conductor than is possible when single-conductor cables were drawn into one duct.

Types of Insulation. — Three different materials are used in the insulation of cables, viz., rubber, varnished cambric, and impregnated paper. Rubber and varnished cambric are used chiefly at voltages below 5000, and impregnated paper is used extensively at all the voltages commonly used in light and power service. Rubber finds its most useful field where no lead sheath is employed, as in interior wiring.

Properties of Insulating Materials. — *Rubber.* The type of rubber used for insulation is that known, technically, as "hevea rubber," this being a term used to denote an extract whose chemical composition is within certain fixed limits. It is brought to the proper degree of vulcanization and resilience by the use of sulphur and other chemicals, known as accelerators, fillers, and softeners.

The resulting material is made up of approximately 32 per cent hevea rubber, 24 per cent whiting, 35 per cent zinc oxide, 5 per cent litharge, 2 per cent sulphur, and 2 per cent paraffine.

Rubber is subject to deterioration by oxidation, which renders it brittle and hard, and the oxidizing process is hastened by high temperatures, and by ozone liberated by static discharges. It has a high dielectric loss at higher voltages.

For these reasons the A.I.E.E. Standards fix the maximum working temperature for rubber at 60° C., less 1 degree for each 4 kv. of working pressure.

Varnished Cambric. This is made of muslin, coated with a varnish compounded especially to give good insulating and mechanical properties.

It does not absorb moisture as readily as paper and has been used instead of rubber to some extent. It is used quite generally for cables in power stations and substations, where the insulation is exposed to atmospheric moisture.

Its use for underground cables is limited to lower voltages, as it has a higher dielectric loss and lower dielectric strength at pressures over 5000 volts than impregnated paper, though its dielectric loss is not as high as that of rubber.

It has a higher heat radiating capacity than paper, and, under equivalent conditions, at lower voltages, cambric cables can carry somewhat greater loads than paper cables at the same temperature elevation.

The temperature limit fixed by the A.I.E.E. Standards is 75° C., less 1 degree per kv. of working pressure.

Impregnated Paper. Paper made chiefly of used manila rope, and impregnated with oil compounds, has been used for cable insulation. Foreign manufacturers have utilized wood pulp to a considerable extent, and this is now recognized by American specifications as acceptable.

The impregnating compound usually consists of petrolatum, or other products of the petroleum refineries, with resin oil, or other modifying agencies used to give it higher penetrating power and stability. The presence of the resin oils has been found to greatly increase the dielectric loss of paper insulation, and it has been found desirable to reduce its use to a small fraction of the amount formerly used.

The tearing strength of the paper varies with its moisture content, being greatest at from 10 to 15 per cent of moisture. There is 5 to 8 per cent of moisture in the paper when it leaves the final rolls in the mill.

After being dried and impregnated, its strength is from 60 to 70 per cent of its strength under normal air conditions.

The tearing strength, when impregnated, is important as a factor in permitting bending without damage to the paper.

The density, or compactness, of the fibres in the paper has a material influence on the impregnation, as well as on the dielectric strength and losses.

The excellence of paper insulation for high voltages depends largely upon proper selection of paper and compounds, and improvements are being made by manufacturers in these respects from time to time.

Impregnated paper absorbs moisture if exposed to air or water, and must, therefore, be well sealed at terminals and joints by potheads or wiped sleeves.

Impregnated paper insulation withstands a somewhat higher temperature than cambric or rubber insulation.

Manufacture of Paper Cable. — The process of insulating cables with paper consists in wrapping the necessary number of layers of tape around the conductor or conductors. With lower voltage cables, the successive turns are often allowed to overlap; but with higher voltage, this is usually not permitted. The next layers are applied in a similar manner, but with the space between layers staggered sufficiently to prevent more than 2 consecutive layers from "registering."

Overlapping and wrinkling introduce air spaces, which are detrimental in high voltage cables, and often cause failure of the insulation due to ionization of the air.

The conductors making up a multi-conductor cable are taped individually, and are then put through a cabling machine with additional material necessary to fill the voids and to make a cylindrical exterior. The belt taping is then applied over all the conductors.

The reels carrying the insulated conductors are revolved about the axis of the cable and this gives the conductors a spiral pitch sufficient to make them pliable during installation.

The cable is then dried at a temperature of about 100° C.

and placed in a vacuum tank to complete the operation; or, in some cases, the entire drying process takes place in a vacuum.

The impregnating compound is then introduced without removing the cable from the vacuum tank, thus preventing entrance of moist air before impregnation. This requires from 12 to 36 hours or more according to the viscosity of the compounds used and the amount of insulation.

The cable is then ready to have the lead sheath applied, and this is done with as brief an exposure to the air as possible. The sheath is applied by passing the cable through a lead press having an outlet of the proper diameter to give the thickness desired.

Design of Cables. — A cable is designed to conduct electrical energy continuously

(*a*) At a specified voltage.
(*b*) With a specified maximum current load.
(*c*) Under stated conditions of installation and maintenance.

The specified working voltage determines the thickness of insulation, the maximum current fixes the size of the conductor, and the conditions of installation govern the character of the protective covering over the insulation to prevent damage from external sources.

High values of voltage or current also determine largely whether the cable shall be single-conductor or multiple-conductor.

Thickness of Insulation. — At lower voltages, the minimum thickness of insulation is fixed by the requirements of mechanical strength during installation, rather than by the voltage requirements.

The thickness provided for voltages up to 2 kv. is from $\frac{5}{64}$ to $\frac{10}{64}$ inch, in impregnated paper cables, the greater amounts being used on cables having the larger conductors.

The dielectric strength of impregnated paper in layers is from 300 to 700 volts per mil, the lower value applying to the higher voltage cables.

It is found, however, that when impregnated paper, applied in layers, is subjected to stresses higher than about 50 volts per mil, there is a tendency to overstress the air in the interstices of the paper taping, thus producing local heating, which, in turn, reduces the strength of the dielectric. Some weeks or months may pass after the cable is put into service before failure occurs, the time being shorter as the amount of the overstress is greater.

The puncture voltage is, therefore, usually from 7 to 12 times the operating voltage.

The test pressure applied to detect defects in manufacture at the time of acceptance of the cable is usually from 3 to 5 times the working pressure, the lower ratio applying to the higher voltages. A 35 kv. cable is tested at about 100,000 volts at the cable factory.

The thickness required for puncture at 35 kv. with a stress of 400 volts per mil is $t = \frac{35,000}{400} = 87.5$ mils.

With a ratio of 7 this becomes $7 \times 87.5 = 613$ mils, or $\frac{40}{64}$ inch. This is the total thickness, one-half or $\frac{10}{32}$ being placed on each conductor of a three-conductor cable.

In certain cables, made for use at voltages above 100 kv., the paper insulation is kept impregnated with a fluid oil compound by the use of a central core, which is filled after the air has been exhausted from the cable by a vacuum pump.

This keeps the insulation and all interstices wholly filled with the oil at all times and makes possible a considerable

increase of dielectric stress, as compared with the usual type of impregnated insulation.

The practice of different manufacturers, with regard to the thickness of insulation required, has varied considerably, but with the better knowledge of the properties of impregnating compounds, the practice has become more nearly uniform.

The values of insulation thickness and the corresponding stress in volts per mil at normal working pressures commonly used in American practice are set forth in the following table:

Volts between conductors	Thickness, conductors		Thickness, belt		Volts per Mil	
	64ths inch	Mils	64ths inch	Mils	Conductors	To ground
2,500	6	93.7	4	62.5	13.35	9.2
5,000	8	125.0	4	62.5	20.0	15.4
7,000	9	140.6	5	78.1	24.9	18.4
14,000	13	203.0	5	78.1	34.5	28.8
25,000	18	281.2	8	125.0	44.5	35.5
35,000	20	312.5	8	125.0	56.0	46.2

The thickness of the belt insulation as given in the table applies only to systems operating with the neutral grounded. In an ungrounded system the full voltage between phases is imposed from conductors to ground on two conductors when the third is grounded through a fault or otherwise. It is, therefore necessary to provide as much insulation to ground as between phases in an ungrounded system.

At voltages above 35,000 the diameter of a three-conductor cable having conductors of 300,000 c.m. or larger is greater than it is possible to safely draw into the $3\frac{1}{2}$ inch duct, which is the general standard in American practice. For this and other reasons cables installed for operation at 66 kv. in America have been made single-conductor cables.

Voltage Stress. — In a single-conductor cable, the voltage stress in kv. per cm. is known for any point x within the insulation from the formula

$$\text{Kv. per cm.} = \frac{.577\,E}{x \log_e \frac{D}{d}} = \frac{.577\,E}{xG}$$

in which E is the working pressure in kilovolts between phases, D is the diameter outside of the insulation and d is the diameter of the conductor. The point x is measured in centimeters from the center of the conductor, and values of G the "geometric factor" may be taken from the curve for single-conductor cable in Fig. 153.

The maximum stress occurs where x is a minimum, which is at $x = \frac{d}{2}$ and minimum stress occurs at the outer diameter of the insulation where $x = \frac{D}{2}$.

For any system other than the grounded 3-phase, the factor .577 must be replaced by the proper factor to give the voltage to neutral or to ground for such system.

For a single-conductor cable on a 45 kv., 3-phase system having a conductor of 500,000 c.m., with $\frac{20}{32}$ inch paper insulation d = .814 and D = 2.06 inch

$$\frac{T}{d} = \frac{.625}{.814} = .767.$$

From the curve for single-conductor cable, the value of G at .767 is .93. When $x = \frac{d}{2} = \frac{.814 \times 2.54}{2} = 1.03$ cm. the value of the maximum stress $= \frac{.577 \times 45}{1.03 \times .93} = \frac{25.9}{.958} = 27$ kv. per cm.

Minimum stress occurs at the outer edge of the insulation, where $x = \frac{D}{2} = \frac{2.06 \times 2.54}{2} = 2.61$ cm.

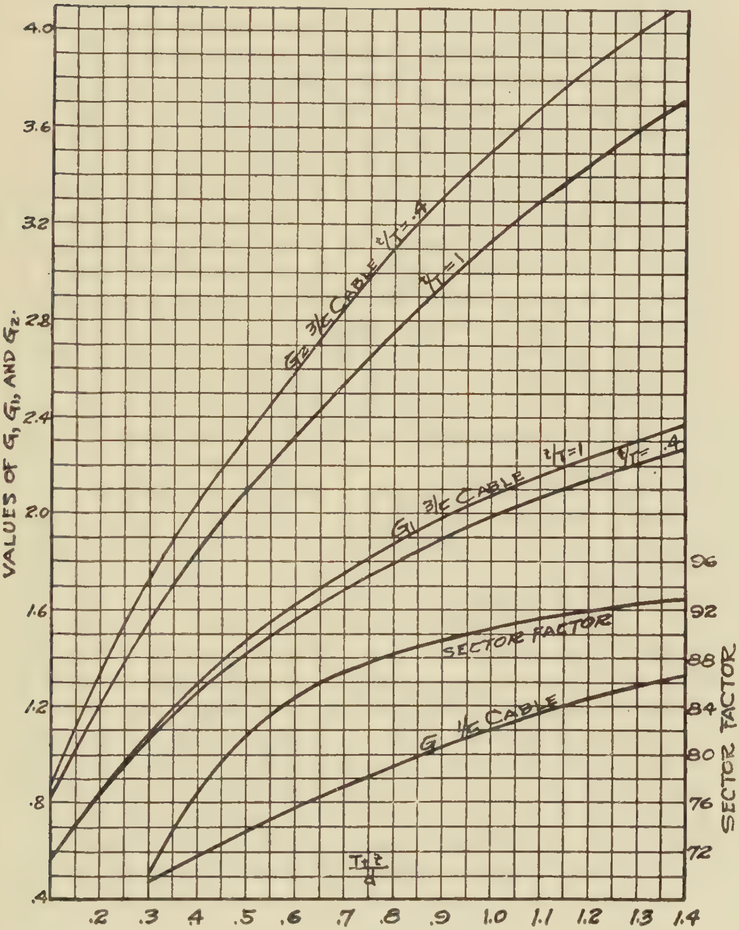


Fig. 153. Geometric Factors.

$$\text{Minimum stress} = \frac{.577 \times 45}{2.61 \times .93} = \frac{25.9}{2.43} = 10.7 \text{ kv. per cm.}$$

In a 3-conductor, 3-phase cable, the stress is modified by the presence of a belt around the 3 conductors and by the proximity of the other phases, and no exact formula has been developed.

But for the types of cables, such as are ordinarily used, D. M. Simons has, with the aid of test data published by R. W. Atkinson, developed a formula for maximum stress of cables having round conductors of the same type as that applying to single-conductor cable.

$$\text{Maximum voltage stress} = \frac{.68\ E}{r \times G_2}$$

in which r is the radius of the conductor (inches) and G_2 is a modified value of the logarithmic term, the numerical values of which may be taken from the curves in Fig. 153.

Simons has termed this the "geometric factor" of a cable, as it varies with the ratio of insulation thicknesses to conductor diameter.

For a 35 kv. cable, having round conductors of 350,000 c.m. ($d = .681$), with $\frac{10}{32}$ inch on conductors and $\frac{4}{32}$ inch as a belt, the ratio $\frac{T+t}{d} = \frac{.312 + .125}{.681} = .64$ and $\frac{t}{T} = .4$.

From the curve, the value of $G_2 = 2.7$. $r = \frac{.681}{2} = .34$.

$$\text{Maximum stress} = \frac{.68 \times 35}{.34 \times 2.7} = \frac{23.8}{.918} = 25.9 \text{ kv. per cm.}$$

Cable Diameters. — The minimum thickness of the lead sheath is varied to suit cables of different over-all diameters, and has been standardized by the A.E.S.C. as follows:

Diameter inside sheath	Thickness of lead sheath
Up to .7 inch	$\frac{5}{64}$ inch
.71 to 1.35 "	$\frac{6}{64}$ "
1.36 to 1.95 "	$\frac{7}{64}$ "
1.96 to 2.50 "	$\frac{8}{64}$ "
2.51 to 3.00 "	$\frac{9}{64}$ "
Over 3.00 "	$\frac{10}{64}$ "

The diameter of a cable D may be calculated from the size of conductor d, the thickness of conductor insulation T, the thickness of belt insulation t, and the thickness of the lead S, as follows:

Single-Conductor $D = d + 2\,T + 2\,S$.
Two-Conductor $D = 2\,(d + 2\,T + t + S)$.
Three-Conductor $D = 2.154\,(d + 2\,T) + 2\,(t + S)$.
Four-Conductor $D = 2.414\,(d + 2\,T) + 2\,(t + S)$.

These formulas apply to cables with round conductors and are not applicable to cables having concentric or sector conductors. The reduction in diameter due to the sector shape is greatest with 2-conductor cables of the D type having large conductors, being about 30 per cent for a cable having conductors of 1,000,000 c.m. For a 3-conductor sector cable of 350,000 c.m. the diameter is about $D - .35\,d$ when D is the diameter of the cable with round conductors and d is the equivalent round diameter of one conductor.

The diameters of bare stranded cables are given in Chapter XIV.

Dielectric Loss. — Impregnated paper, when subjected to high-voltage stresses at high temperatures, absorbs energy which appears as heat in the insulation. The heat developed in certain types of cable insulation has been sufficient

to materially reduce the amount of energy which the cable can safely be permitted to carry.

The amount of the dielectric loss varies with the frequency, voltage, and temperature. At a given frequency and voltage it varies with the temperature, increasing quite rapidly at temperatures above 50° C. This is shown by the curves in Fig. 154, giving results of tests on two 20 kv. cables, one of

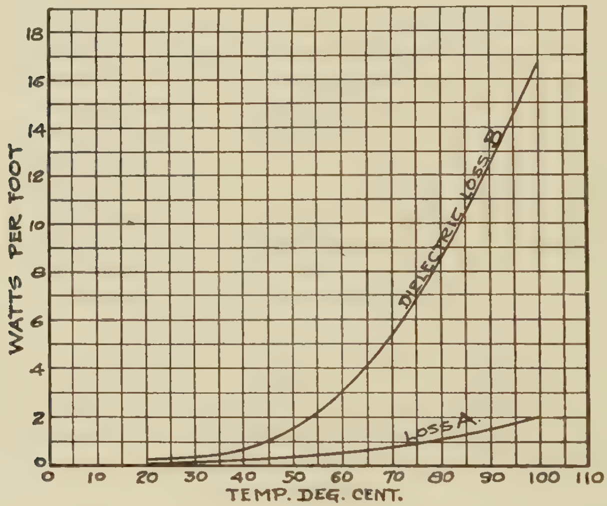


Fig. 154. Dielectric Loss Variation.

them, cable *B*, having a high dielectric loss. It will be seen that the loss in the insulation of this cable at 87° C. is about 11 watts per foot, while the loss in *A* at that temperature is 1.35 watts.

The copper loss of this cable, at a load which would normally be considered its safe maximum load, was about 7 watts. The effect of the dielectric loss would, therefore, be to so greatly increase the temperature rise, at full load, as to reduce the safe carrying capacity of the cable to a fraction of its normal value.

The sharp up-turn of the curve of cable B may bring the cable beyond the critical state, where the dielectric loss increases faster than the heat is radiated from the cable, and the temperature increases in a cumulative manner until the insulation is carbonized and the cable fails.

This cable was impregnated with compound having a large proportion of rosin oil, and such compounds have been found to have high values of dielectric loss, as have also cables insulated with varnished cambric. Compounds having a low percentage of rosin oil, with a great predominance of mineral oils, have produced insulation in which the dielectric loss is reduced to practically negligible values when operated at pressures below 15,000 volts. At higher pressures, the dielectric loss is usually kept below one watt per foot at the maximum permissible temperature of the insulation.

Charging Current. — The electrostatic charging current per 1000 feet is

$$I_c = \frac{.106\, efnk}{G} \text{ milliamperes}$$

in which e is the voltage to neutral in kv., f is the frequency, n is the number of conductors, k is the specific inductive capacity and G is the geometric factor as given in the curves in Fig. 153.

The specific inductive capacity of impregnated paper is 3.3; for varnished cambric it is 4.5 and for rubber it is 5.5.

On a 60-cycle three-phase system with impregnated paper cable the charging current of a three-conductor cable becomes

$$I_c = \frac{.106\, E \times 60 \times 3 \times 3.3}{1000 \times 1.73\, G} = \frac{.0364\, E}{G} \text{ amperes per 1000 feet.}$$

For a single-conductor paper cable the charging current is

$$I_c = \frac{.106\, E \times 60 \times 3.3}{1000 \times 1.73\, G} = \frac{.0121\, E}{G} \text{ amperes per 1000 feet.}$$

Illustration. — What is the charging current of a 3-conductor impregnated paper cable having sector type conductors of 350,000 c.m. insulated with $\frac{10}{32}$ inch on each conductor and $\frac{4}{32}$ inch on the belt, when operating at 60 cycles on a 33,000 volt three-phase system?

For such a cable the equivalent diameter of the conductor is $d = .681$. $T = .312$. $t = .125$. $t/T = .4$

$\frac{T + t}{d} = \frac{.312 + .125}{.681} = .64$ for which $G = 2.7$ from the curve. The sector factor being .855 the value of $G = 2.7 \times .855 = 2.31$

$$I_c = \frac{.0364 \times 33}{2.31} = .52 \text{ ampere per 1000 ft.}$$

For a single-conductor cable with a 500,000 c.m. conductor carrying $\frac{20}{32}$ inch of paper insulation at 45,000 volts, 60 cycles, the charging current is as follows: $d = .814$. $T = .625$.

$$\frac{T}{d} = \frac{.625}{.814} = .76. \quad \text{From the curve, } G = .93$$

$$I_c = \frac{.0121\ E}{G} = \frac{.0121 \times 45}{.93} = .585 \text{ ampere per 1000 ft.}$$

Dielectric Loss and Power Factor. — The leakage current of a cable at no load but under normal pressure, is the resultant of the charging current and the dielectric loss current. The power factor of the leakage current therefore varies with the dielectric loss in cables having similar geometric factors, and becomes of importance in making comparisons of cables. The dielectric loss per foot in a single-conductor cable is $W = \frac{1000\ I_d E}{1.73}$ when it is on a 3-phase system.

The dielectric loss current per mile is $I_d = \frac{1.73 \times 5280\, W}{1000\, E} = \frac{9.13\, W}{E}$ amperes, for a single conductor cable. E is in kv.

For a 3-conductor cable $W = \frac{1000 \times 3\, I_d E}{1.73} = 1730\, I_d E$ and the dielectric loss current per mile is $I_d = \frac{5280\, W}{1730\, E} = \frac{3.05\, W}{E}$ amperes.

If the three-conductor 33 kv. cable, for which the charging current was found in the foregoing section to be .52 ampere per mile, has a dielectric loss of 1 watt per foot the loss component of the leakage current is $I_d = \frac{3.05 \times 1}{33} = .092$ ampere per mile.

The leakage current is

$$I = \sqrt{I_c^2 + I_d^2} = \sqrt{(.52)^2 + (.0924)^2} = .528$$

and the power factor of the leakage current is $\frac{.0924}{.528} = .0175$ or 1.75 per cent.

In the case of the single-conductor cable at 45 kv. if the dielectric loss is .5 watt per foot the loss current is

$$I_d = \frac{9.13\, W}{E} = \frac{9.13 \times .5}{45} = .1015 \text{ ampere per mile.}$$

Since the charging current was found to be .59 ampere $I = \sqrt{(.59)^2 + (.1015)^2} = .594$ ampere per 1000 ft. and the power factor is $\frac{.1015}{.594} = .017$ or 1.7 per cent.

Current-carrying Capacity. — In low-tension distribution, in underground transmission cables and in other situations

where the size of the conductor is not determined by the permissible line drop, the load of the conductor is usually fixed by the heating of the cable.

The heating of cables in a conduit system introduces various limitations which must be recognized in the design and operation of the line.

(*a*) With cables having large copper areas, the expansion and contraction of the cable in the duct is sufficient to necessitate the use of suitable shields at the duct mouth in manholes. Damage to sheaths followed by introduction of moisture and failure of the insulation has resulted in such cables where suitable protection had not been provided.

(*b*) The effect of dielectric loss in high-voltage cables is greatly increased at temperatures above 75° C., and must be guarded against by limiting loads on old cables having high losses and by having a low dielectric loss in new cables.

(*c*) In large duct lines carrying many loaded cables, the temperatures in manholes may become so high as to make it difficult to do necessary work in them. Temperatures above 100° F. are often found in such manholes when first opened, and some means of artificial ventilation may be required to permit men to remain in the hole long enough to do their work.

(*d*) The effect of temperature on the life of cable insulation is, of course, of great importance, and has been given the attention of cable manufacturers and cable users.

Temperature Limits. — The maximum temperature at which cable insulation should be operated is fixed for cables operated below 5 kv. by the effect of temperature on the life of the insulation.

At higher voltages the dielectric loss and other factors are affected by higher temperatures in sufficient amount to necessitate further restriction of the maximum temperature limit, in proportion to the working voltage.

For impregnated paper insulation, the A.I.E.E. Standards therefore state that the maximum temperature shall not exceed $90 - E°$ C., when E is the working pressure expressed in kv. It is further provided that E shall be considered as 5 for all cables working at or below 5 kv. and as 30 for all cables working at or above 30 kv. In effect this fixes the maximum temperature for low-tension cables at 85° C. and for cables at 30 kv. or higher at 60° C.

For varnished cambric and rubber cables the use of which at voltages above 10 kv. is limited by their high dielectric loss the temperature limits are

Varnished Cambric	$75 - E°$ C.
Rubber Cambric	$60 - .25\, E°$ C.

The temperature of a cable in an underground conduit is determined by three principal factors.

(*a*) The watts lost in the conductor and its insulation.
(*b*) The thermal resistance of the insulation, sheath, and duct system.
(*c*) The temperature of the soil in which the conduit is laid.

The rise of temperature in the cable and duct system is

$$T = RW.$$

R is the total thermal resistance of the cable and duct system, and W is the loss in watts per foot dissipated as heat.

The loss per foot is the sum of the I^2R loss in all the conductors of the cable and the dielectric loss in the insulation.

The thermal resistance is in two parts, viz., that of the cable insulation and sheath, and that of the duct structure.

The thermal resistance, R_2, of the insulation and sheath of any cable, multiplied by W_2, the watt loss per foot in such cable is T_2, the rise in temperature from duct to copper, or

$$T_2 = R_2W_2.$$

The rise in temperature from soil to duct is

$$T_1 = R_1W_1,$$

when R_1 is the thermal resistance from duct structure to soil, and W_1 is the sum of the watts lost per foot in all the cables in the conduit line.

The copper temperature is $T = T_1 + T_2 + T_0$, when the soil temperature is T_0.

The value of the duct temperature $T_1 + T_0$ may be determined by thermometer readings taken in an empty duct, or by calculation, if the soil resistance and average watts per foot of the conduit line are known.

Thermometer readings may be taken by inserting a suitable instrument into an empty duct for a distance of 20 feet or more.

Such readings vary somewhat in different parts of the duct line, and maximum temperatures are usually somewhat higher than thermometer readings.

Much of the heat liberated by the cables of a conduit line is stored in the cable and conduit structure, and requires from 6 to 12 hours to bring the duct structure up to a stable temperature.

In practical cases loads are not steadily maintained, and the watts liberated vary from hour to hour throughout the day in some such manner as that illustrated by the curves in Fig. 155.

These show the watt losses in a 9-duct line carrying six 13-kv. cables which supply an industrial load throughout the daylight hours and a lighting load of approximately the same amount in the evening.

There is an average rise of duct temperature from the soil temperature of 9° C. to about 30° C.

It will be seen that the maximum temperature is reached between 12 P.M. and 3 A.M., about 9 hours after the middle

of the heavy load period, and the minimum temperature is from 7 to 10 A.M., about 6 hours after the middle of the period of lowest load.

It is evident that the conduit has insufficient time to cool off or heat up during a 24-hour period, except within the narrow range of about 3 degrees. This makes it possible to determine, within a few degrees, the permissible rise of tem-

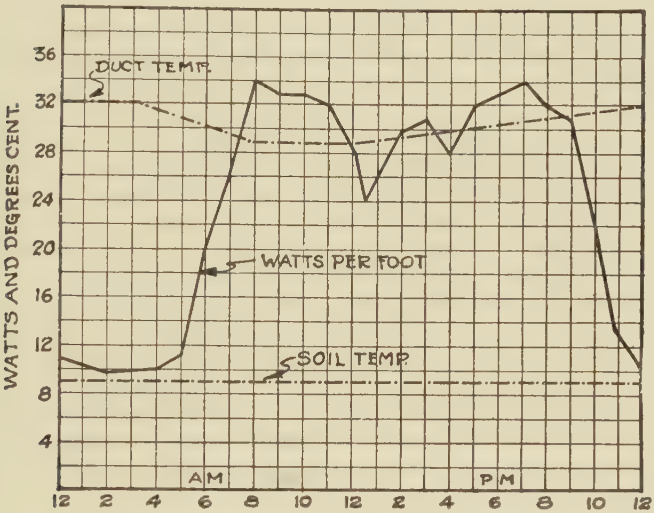


Fig. 155. Heating of Ducts.

perature, and thence the carrying capacity of the cables by means of temperature surveys made through the usual range of soil temperatures.

Soil Temperature. — The temperature of the soil varies throughout the year, the range depending somewhat upon the latitude.

Observations made in Washington, D. C., show a minimum soil temperature in January and February of about 4° C., and a maximum of about 30° C. in July and August. These

temperatures were taken from thermo-couples buried in the soil at the usual depths at which conduits are laid, 27 to 36 inches.

In latitudes farther north the soil freezes to a depth of 1 to 3 feet in January and February, and winter soil temperatures of 0° C. are commonly experienced. Summer temperatures are from 20° to 30° C., the maximum usually being reached early in September.

Thermal Resistance of Cable. — The resistance of impregnated paper and lead sheath to the flow of heat may be computed from the formula

$$R_2 = \frac{.00522\, rG_1}{n} + \frac{.00411\, B}{D} \text{ thermal ohms per ft.}$$

In this equation r is the thermal resistivity of impregnated paper and has an average value of 850. B is the thermal resistivity of the lead sheath and has an average value of 200. n is the number of conductors in the cable and D is the outside diameter of the cable in inches. G_1 is the geometric factor for heating as taken from the curves in Fig. 153.

Substituting these values the equation may be reduced to

$$R_2 = \frac{4.44\, G_1}{n} + \frac{4.93}{D} \text{ thermal ohms per foot.}$$

The expression $\frac{4.44\, G_1}{n}$ represents the thermal resistance of the insulation and $\frac{4.93}{D}$ is the thermal resistance of the sheath.

The sum of these is the resistance to heat from the copper conductor to the air in the duct system.

The thermal resistance from the air in the duct to the soil varies with the character of the soil and is much lower at

times when the percentage of moisture is above 5 per cent than at lower values.

When the thermal resistivity and approximate moisture content of the soil are known the thermal resistance from duct to soil may be computed from the formula

$$R_1 = .00522\, r' \log \frac{4\,d}{L} \text{ thermal ohms per ft. of duct.}$$

In this equation r' is the thermal resistivity of the soil, which for percentages of moisture between 8 and 14 in a sandy soil may be taken at 100, though it may be as high as 300 for soils containing less than 5 per cent of moisture.

d is the depth of the axis of the duct structure below the surface, L is the length of one side of a square of area equal to that of the cross-section of the duct structure.

This formula may be stated in terms of the logarithm to base 10, as follows:

$$R_1 = .00522 \times 2.302\, r' \log \frac{4\,d}{L} = .012\, r' \log_{10} \frac{4\,d}{L}\,.$$

Illustration of Cable Temperature Calculations. — Assume conditions as follows:

A 12-duct conduit, laid at a depth of 42 inches from surface of soil to center line of conduit, 21.5 × 27 inches, making the side of an equivalent square about 24 inches. Soil having a thermal resistivity of 100° C per watt per cu. cm.

Three 13 kv. cables with 3 sector conductors of 500,000 c.m. having a conductor resistance of .000025 ohm per ft. at 65° C. with $\frac{7}{32}$ inch paper insulation on each conductor and $\frac{3}{32}$ inch paper in the belt.

Six 4 kv. cables, 3 conductor, 211,000 c.m. having a conductor resistance of .0000587 ohm per ft. at 65° C. with $\frac{4}{32}$ inch paper on each conductor and $\frac{2}{32}$ inch paper in the belt.

The cables carry ampere loads for a sufficient length of

time to bring them to a stable temperature and have losses as indicated in the following table:

No.	Kv.	Amperes	Watts loss per foot		
			Copper	Dielectric	Total
1	13	310	7.2	1.0	8.2
2	13	250	4.7	.6	5.3
3	13	163	2.0	.4	2.4
4	4	114	2.3	...	2.3
5	4	170	5.1	...	5.1
6	4	101	1.8	...	1.8
7	4	151	4.0	...	4.0
8	4	220	8.5	...	8.5
9	4	117	2.4	...	2.4
			38.0	2.0	40.0

The dielectric losses in the 13 kv. cables are chosen with reference to their respective temperatures at the loads assumed.

For the 13 kv. cable $\frac{T + t}{d} = \frac{.2187 + .0938}{.814} = .383$.

The value of G_1 for heating is $1.24 \times .76$ (sector factor) $= .942$ (Fig. 153). Diameter inside sheath $= 2.154\ (.814 + .437) + .187 = 2.88$ inches less the correction for sector shape of $.35 \times .814 = .285$, or 2.595 inches. Adding $2 \times .14 = .28$ for the lead sheath $D = 2.875$ inches.

$$R_2 = \frac{4.44\,G_1}{3} + \frac{4.93}{D} = \frac{4.44 \times .942}{3} + \frac{4.93}{2.875} = 1.39 + 1.71 = 3.1.$$

For the 4 kv. cable $\frac{T + t}{d} = \frac{.125 + .0625}{.528} = .355$.

From Fig. 153, $G_1 = 1.19$.

$D = 2.154\ (.528 + .25) + .125 + .25$ (sheath) $= 2.05$ inches.

$$R_2 = \frac{4.44 \times 1.19}{3} + \frac{4.93}{2.05} = 4.16.$$

The first step in the calculation is the determination of

the duct temperature under the assumed rate of heat dissipation of 40 watts per foot of conduit.

This being known, the permissible rise above duct temperature for paper cables at the voltages assumed is found.

From the rise of temperature in the cable itself the permissible ampere load may be determined.

The thermal resistance of the 12 duct conduit is

$$R_1 = .012\, r' \log \frac{4\,d}{L} = .012 \times 100 \times \log \frac{168}{24} = 1.013.$$

The rise of temperature in the duct is

$$T_1 = R_1 W = 1.013 \times 40 = 40.5^\circ \text{ C.}$$

The duct temperature is the sum of the soil temperature $T_0 + T_1$, the rise in the duct.

The permissible total rise in temperature for the 13 kv. cables is $90 - 13 = 77^\circ$ C. and the rise in the cable itself is $T_2 = 77 - (T_0 + T_1)$.

When the soil temperature is 0° C. $T_2 = 77 - (0 + 40.5) = 36.5^\circ$ C. At 10° C. soil temperature $T_2 = 26.5^\circ$ C. etc.

The permissible value of T_2 being known for any given soil temperature the loss in watts per foot which will produce a rise of T_2 degrees is $W_2 = \dfrac{T_2}{R_2}$.

The loss per foot in the case of cable No. 1 is made up of 1 watt of dielectric loss and a copper loss which varies as the square of the current carried by the cable.

$$W_2 = W_d + W_c.$$

The rise of temperature from the air in the duct to the conductor is thus caused by two sources of heat, one of which arises within the conductor and one within the insulation.

In determining the permissible value of the heat arising within the conductor the loss due to the insulation must be deducted from the total loss.

For cable No. 1, $T_2 = 36.5°$ C. at a soil temperature of 0° C. The total loss per foot under this condition is

$$W_2 = \frac{T_2}{R_2} = \frac{36.5}{3.1} = 11.8 \text{ watts per foot.}$$

The dielectric loss per foot being 1 watt in this cable at full load temperature, the copper loss is 11.8 − 1 = 10.8 watts per foot.

$$W_2 = 3\,I^2 r = 3\,I^2 \times .000025 = 10.8$$

$$I^2 = \frac{10.8}{.000075} = 144{,}000. \quad I = 380 \text{ amperes.}$$

This is the maximum permissible current at 0° C. soil temperature. At a soil temperature of 20° C. the permissible rise is reduced to 36.5 − 20 = 16.5° C.

$$W_2 = \frac{16.5}{3.1} = 5.32 \text{ watts per foot.}$$

$$I^2 = \frac{5.32}{.000075} = 71.000. \quad I = 266 \text{ amperes.}$$

It is thus apparent that under summer soil temperatures cable ratings in loaded conduit lines should be materially reduced. In many cases soil moisture conditions in the summer months accentuate this situation and necessitate special ventilation of ducts or other means of cooling.

In the case of the 4 kv. cables the maximum permissible temperature of paper insulation is 90 − 5 = 85° C. and the permissible rise above duct temperature at 0° C. soil temperature is 85 − 40.5 = 44.5° C.

$$W_2 = \frac{44.5}{4.16} = 10.7 \text{ watts per foot}$$

$$W_2 = 3\,I^2 \times .0000587 = 10.7 \text{ watts per foot}$$

$$I^2 = \frac{10.7}{.000176} = 60.800. \quad I = 246 \text{ amperes.}$$

At a soil temperature of 20° C. the permissible rise is $45.5 - 20 = 25.5°$ C. For this condition

$$W_2 = \frac{25.5}{4.16} = 6.13 \text{ watts per foot}$$

$$I^2 = \frac{6.13}{.000176} = 34.800. \quad I = 186 \text{ amperes.}$$

The temperature of the several cables assumed as being in operation in this 12-duct conduit at usual soil temperature is of interest.

Taking cable No. 8 for instance, the loss is 8.5 watts per foot and the thermal resistance for 4 kv. cables has been found to be 4.16.

The temperature rise above the duct is therefore

$$T_2 = W_2R_2 = 8.5 \times 4.16 = 35.3° \text{ C.}$$

The temperature of the copper is

$T = 35.3 + 40.5 + 10 = 85.8°$ C. at a soil temperature of 10° C. or 75.8° C. at a soil temperature of 0° C.

The temperature of these cables at the loads assumed and with soil temperatures of 0° and 20° C. respectively are as follows:

No.	Amperes	Watts per foot	W_2R_2	Temp. of copper, deg. C.	
				$T_0 = 0°$ C. $T_1 = 40.5°$ C.	$T_0 = 20°$ C. $T_1 = 40.5°$ C.
1	310	8.2	25.4	65.9	85.9
2	250	5.3	16.4	56.9	76.9
3	163	2.4	7.4	47.9	67.9
4	114	2.3	9.5	50.0	70.0
5	170	5.1	21.2	61.7	81.7
6	101	1.8	7.5	48.0	68.0
7	151	4.0	16.6	57.1	77.1
8	220	8.5	35.3	75.8	95.8
9	117	2.4	10.0	50.5	70.5

It will be noted that cables No. 1 and No. 8 are both heated beyond the safe temperature for the insulation when the soil temperature is at 20° C. or at any other temperature above 10° C.

Duct Radiation. — The foregoing formulas for temperature rise under full load are based on the assumption that the conduit structure and the earth are of the same general character as regards heat resistance.

However, it is apparent that the ducts in the center of a large conduit line, which have no contact with the earth but must depend on the heat conductivity of adjoining ducts, will necessarily have a higher thermal resistance from duct to soil than those around the perimeter of the conduit section.

The calculation of this difference is complicated by the irregular shape of the parts of the duct through which such

100	100
100	100

93	79	93
79	64	79
93	79	93

89	71	71	89
71	48	48	71
71	48	48	71
89	71	71	89

95	95
83	83
83	83
95	95

91	77	91
75	60	75
75	60	75
91	77	91

Fig. 156. Current Capacity Factors.

heat must travel to reach the outside. However, temperature readings taken in such ducts under known conditions of load give an indication of the situation, which it is useful to have in mind.

Mr. P. Torchio has made a diagram, partially reproduced

in Fig. 156, which shows the percentage of full-load current which can be carried by a cable placed in the various ducts of different formations. Full load current is taken as that which the cable can safely carry when in a 4-duct line.

Sheath Currents. — In a single conductor cable there is an induced voltage in the lead sheath which is proportional to the current carried by the cable. In a line 1 or more miles in length, the induced voltage under full load may reach dangerous values if the sheaths of adjacent cables are insulated from each other.

It is, therefore, usually found preferable to ground and bond the cable sheaths together, permitting the short-circuited current to flow through the sheath. This has the effect of making the apparent resistance higher than the copper resistance, and of proportionately increasing the energy loss in the cable.

The total apparent resistance, when the sheath currents are permitted to flow, is

$$R + R_0 = R + \frac{X^2 R_s}{X^2 + R_s^2} \text{ ohms per 1000 feet.}$$

In this formula R is the resistance of the copper conductor, X is the mutual reactance of the lead sheath, as related to the conductor, and R_s is the sheath resistance.

The mutual inductance of the sheath to neutral is

$$M = .1404 \log \frac{2\,S}{r + r_1} \text{ millihenries per 1000 feet,}$$

in which S is the distance between the conductors of the circuit, r is the radius of the inner diameter of the lead sheath, and r_1 is the radius of the outer diameter of the sheath. At a frequency of 60 cycles

$$X = \frac{6.28 \times 60\,M}{1000} \text{ ohms per 1000 feet.}$$

The sheath resistance is

$$R_s = \frac{.0378}{r_1^2 - r^2} \text{ ohms per 1000 feet.}$$

This is based on a resistivity of 25.2 for lead at 50° C.

For example, the effective resistance of a circuit consisting of three 500,000 c.m. single-conductor cables, designed for 45 kv., and having $\frac{20}{32}$ inch insulation and $\frac{4}{32}$ inch lead sheath, 3 phase, 60 cycles, 5 inch separation, is as follows:

$r_1 = 1.157. \quad r = 1.032.$

$$M = .1404 \log \frac{2 \times 5}{1.157 + 1.032} = .0926 \text{ m.h. per 1000 feet.}$$

$$X = \frac{6.28 \times 60 \times .0926}{1000} = .0349 \text{ ohm per 1000 feet.}$$

$$R_s = \frac{.0378}{(1.157)^2 - (1.032)^2} = .138 \text{ ohm per 1000 feet.}$$

At 60° C., the copper resistance $R = .0245$ ohm per 1000 feet.

$$R_0 = \frac{X^2 R_s}{X^2 + R_s^2} = \frac{(.0349)^2 \times .138}{(.0349)^2 + (.138)^2} = .0083 \text{ ohm per 1000 ft.}$$

$R + R_0 = .0245 + .0083 = .0328$ ohm per 1000 feet. Thus, the apparent resistance is $\frac{.0083}{.0245} = 33.8$ per cent higher than the copper resistance.

The induced sheath voltage is $E_s = IX = .0349$ volt per ampere of current carried by the conductor per 1000 feet.

With a line carrying 300 amperes, the induced voltage, if not bonded, would be

$$300 \times .0349 = 10.47 \text{ volts per 1000 feet.}$$

The sheath current in such a line, when bonded, is

$$I_s = \frac{300 \times .0349}{\sqrt{(.0349)^2 + (.138)^2}} = 73.5 \text{ amperes.}$$

The ratio of sheath current to load current is $\frac{73.5}{300} = 24.5$ per cent.

The loss in the sheath when 73.5 amperes are flowing is $I_s^2R_s = (73.5)^2 \times .138 = 745$ watts per 1000 feet.

The loss in the conductor at 300 amperes is $I^2R = (300)^2 \times .0245 = 2205$ watts per 1000 feet.

The total loss is 2950 watts per 1000 feet, and the ratio of total loss to conductor loss is $\frac{2950}{2205} = 1.338$.

The heating of this cable is increased by the loss in the sheath, and the temperature rise due to the sheath loss must be added to that due to the current carried by the conductor.

$$T_2 = W_2R_2 = W_2\left(4.44\, G_1 + \frac{1.338 \times 4.93}{D}\right) \text{degrees C.}$$

It is to be noted that only that part of the thermal resistance which is due to the sheath is affected by the sheath loss.

In this cable $D = 1.157 \times 2 = 2.31$ inches, and the thermal resistance of the sheath is $\frac{4.93}{2.31} = 1.7$.

This is increased to an effective value of $1.7 \times 1.338 = 2.28$ by the sheath loss. $\frac{T + t}{d} = \frac{.625}{.814} = .77$, and the value of G_1 for single-conductor cable is .92 (Fig. 153).

The total thermal resistance is

$$R_2 = 4.44 \times .92 + 2.28 = 4.07 + 2.28 = 6.35.$$

With no sheath loss this would be $4.07 + 1.7 = 5.77$, and the heating of the cable is, therefore, increased by the ratio $\frac{6.35}{5.77} = 1.1$, and its carrying capacity is reduced about 5 per cent, by the sheath loss.

The following is a partial bibliography of papers dealing with power cables, which contain valuable detailed information regarding the subjects discussed in the foregoing chapter.

Cable Insulation.

1917 — A.I.E.E. Trans. Page 447. Clark and Shanklin. Insulation Characteristics of High Voltage Cables.

1919 — A.I.E.E. Trans. Page 971. Atkinson. Dielectric Field in an Electric Power Cable.

1921 — A.I.E.E. Trans. Page 12. Davis and Simons. Maximum Allowable Working Voltage in Cables.

1922 — A.I.E.E. Trans. Page 547. Roper. Dielectric Losses and Stresses in Relation to Cable Failures.

1922 — A.I.E.E. Trans. Page 570. Middleton, Dawes, and Davis. Potential Gradient in Cables.

Current Carrying Capacity and Heating.

1917 — A.I.E.E. Trans. Page 431. Bang and Louis. Influence of Dielectric Loss on the Rating of High-Tension Cables.

1921 — A.I.E.E. Pages 97–137. Symposium by Delmar, Torchio, Elden, Roper, Clark, Fisher, and Atkinson on "Safe Operating Temperatures of Oiled Paper Insulation at Low Tensions."

1922 — A.I.E.E. Page 94. Shanklin. Effect of Moisture on the Thermal Conductivity of Soils.

1923 — A.I.E.E. Page 600. Simons. Calculation of Current Carrying Capacity.

1925 — Electric Journal. Page 366. Simons. Calculation of Problems of Transmission by Underground Cables (including extended bibliography of papers on cable subjects in Europe and America up to 1925).

CHAPTER XIII

INSTALLATION OF CABLES

Methods. — Cables used for the distribution of electricity in America are usually placed in a conduit system. In Europe they are usually placed directly in the ground without provision for withdrawal except by excavation, though draw-in systems have been introduced in later years for lines in groups near power stations.

The use of draw-in systems in America has been general since the use of lead cables began to supersede extensions of Edison tube systems. The rapid growth of American cities necessitates annual reinforcement of feeder systems and with built-in systems there is an amount of re-excavation and repaving which is not only too expensive as compared with draw-in systems, but becomes a source of complaint by municipal authorities and the public.

Where one or two cables are laid in parkways for scattered service, such as street lighting in residence districts, the use of armored cable laid directly in the soil is economical and practical. Such cables are also employed to advantage at river crossings where the laying of ducts is difficult and there are but few cables. Where many cables are carried across a stream a tunnel is often the most practical solution of the problem. Where one or two cables are carried from one parkway to another under expensive paving it is sometimes found desirable to lay iron pipe for the section under the paving. This is also useful at railroad crossings, bridges, and similar situations where access for repair work is difficult.

These installations are, however, usually regarded as

special expedients employed only where the use of a conduit system is not feasible or is too expensive.

The major part of the cable installed goes into conduit systems and the practice followed in making cable installations in conduit systems will be considered in some detail in this chapter.

Duct Assignments. — The assignment of the cables used for the various parts of an electric service system to the respective ducts of the conduit is of importance. A standard practice should be worked out and followed as closely as possible in order that uniformity of conditions may be had in manholes. Such a policy is very important in the larger systems where different crews of men are doing work in manholes from time to time, and a uniform arrangement saves time in doing work as well as in promoting safety.

On streets where there are local distribution mains, distribution feeders and perhaps transmission cables, it is found to be good practice to use the top row of ducts for the local service, the outside rows on the sides for distribution feeders and the bottom row for transmission cables, if any. Ducts in the center of the conduit should be used as far as practicable for cables carrying small currents where heat radiation is not a factor, such as pilot wires of balanced relays, pressure wires of low-tension networks, series lighting circuits and the like.

The distributing mains are placed in the top row, so that they are accessible to service handholes without opening the lower ducts into the handhole.

Feeders and transmission lines usually carry long hour loads which produce accumulated heat in the conduit. This is best radiated to the soil from the side and bottom ducts.

The use of the side ducts for cables going through manholes without taps facilitates training around the walls and promotes an orderly arrangement.

Such cables are carried below junction boxes which are usually placed as near the roof of the manhole as is feasible.

The assignment of cables to the proper ducts is thus seen to be the first step in making a cable installation.

Selection of Routes. — The selection of routes for distribution feeders and through transmission cables should receive attention where the conduit system is so general as to afford a choice of routes.

The concentration of cables which unavoidably occurs in the immediate vicinity of large generating stations and to a lesser degree near sub-stations may be offset to some extent by providing several conduits of smaller size, thus limiting the number of cables in a given duct run, and giving some choice of routes. In such cases it is desirable to select different routes for cables supplying the same sub-station so that an interruption of service due to a disturbance in a conduit will affect only a part of the lines.

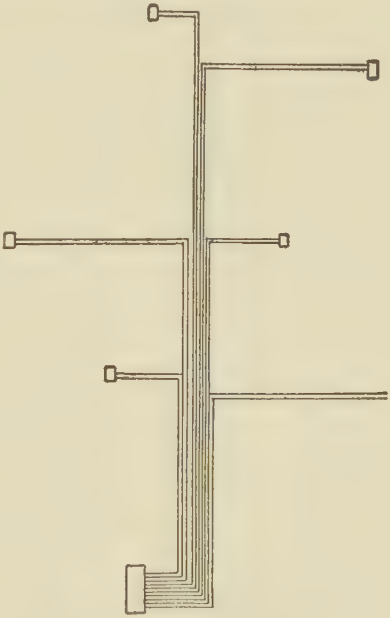


Fig. 157. Lines Routed in Same Duct Lines.

For example with a single main duct run such as that indicated in Fig. 157, the occurrence of a serious disturbance in a manhole or a dislocation of a part of this conduit from any cause might affect both cables to any of the sub-stations

and perhaps to adjacent sub-stations, thus causing a widespread interruption of service.

With an arrangement such as that shown in Fig. 158 the probability of such widespread trouble is largely eliminated.

In the selection of routes for distribution feeders the lengths are shorter and there is less opportunity to select a diversity

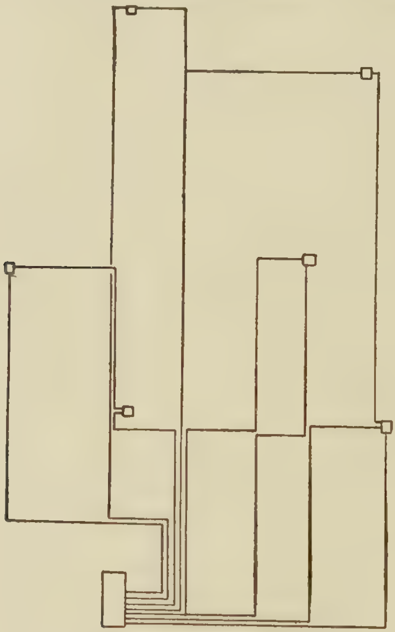


Fig. 158. Lines Routed in Different Duct Lines.

of routes except in the heavy conduit lines near the substation. Feeders going to adjacent areas should be kept in separate conduits as far as it is practicable to do so.

With distribution feeders there is an additional reason for choosing different routes, viz. the fact that feeder ends are being shifted from time to time as load conditions change. When a feeder terminal is re-located it is desirable that its route be along a line where load development is active.

As more feeders are added the use of such routes makes it easier to readjust load centers when feeders become overloaded.

In the case of industrial districts supplied by ring circuits the route of the ring should be chosen in such a way as to bring the circuit as near to other prospective users as is feasible without unduly lengthening the ring.

Installation of Cable. — Cables are received from the manufacturer coiled on reels holding from 500 to 2000 feet of cable, the lengths varying with the size of the cable.

The full reels weigh from 7000 to 10,000 pounds and are often delivered directly from the railroad car to a point near the manhole where the cable is to be drawn in. In the smaller sizes the cable is made up in stock reels from which the required amount is taken as needed.

When the pulling crew arrives the wooden lagging is removed from the reel after it has been placed in the desired position and raised from the ground on a pair of jacks sufficiently to permit it to turn. A bar passed through a hole in the center of the reel serves as an axis of rotation.

In duct lines which have not been rodded it is important to detect the presence of obstructions and remove them before trying to pull in cable. This is done by drawing a mandrel through the duct.

The pulling line is passed through the ducts by the use of detachable rods which are pushed in from one end, being attached one by one as they enter the duct. When the far end has reached the next manhole, the pulling line is attached and the rods are drawn back, and detached as they emerge from the duct, bringing with them the line.

It is sometimes desirable to have rodding work done in advance to conserve the waiting time of a larger crew. Under these circumstances a small wire is drawn through instead of

a pulling line and this wire is made use of to draw the pulling line through when the cable pulling crew arrives.

On pulls up to about 50 eet, such as street crossings and service laterals, a strap of steel known as a " snake " is pushed through in one piece instead of the rods. This is quite a necessary device where service laterals have a bend in them.

The pulling line is of manila rope or steel cable according to the length of the pull and the relative size of the cable as compared with the duct diameter. It is attached to the cable through a pulling eye or by a cable grip of wire mesh.

The wire mesh attachment is most suitable for smaller cables and has the advantage of being attached by merely slipping it over the lead sheath and applying tension to make it grip the cable. On cables which occupy a large part of the duct area this form of grip being outside is likely to cause the cable to stick and the wear is likely to be excessive.

It is therefore usual to employ a pulling eye on large cables. This consists of a collar which is secured to the conductor and is not larger than the cable sheath.

Short lengths are pulled in by man power or in some cases by a capstan as shown in Fig. 159.

In the larger cities trucks are equipped with winches by which the cable is drawn in, using electric motor drive, or in the case of gasoline engine trucks by use of the engine.

There are a variety of methods of rigging the pulley arrangement from the truck into the manhole and to the mouth of the duct. In general they include an arrangement such as that shown in Fig. 160.

The reel of cable is attended by men who pay out the cable at the proper rate to avoid injury to the sheath in entering the manhole and to insure easy entrance to the duct.

When the end has been brought through the operation is slowed down and the cable brought into the manhole with

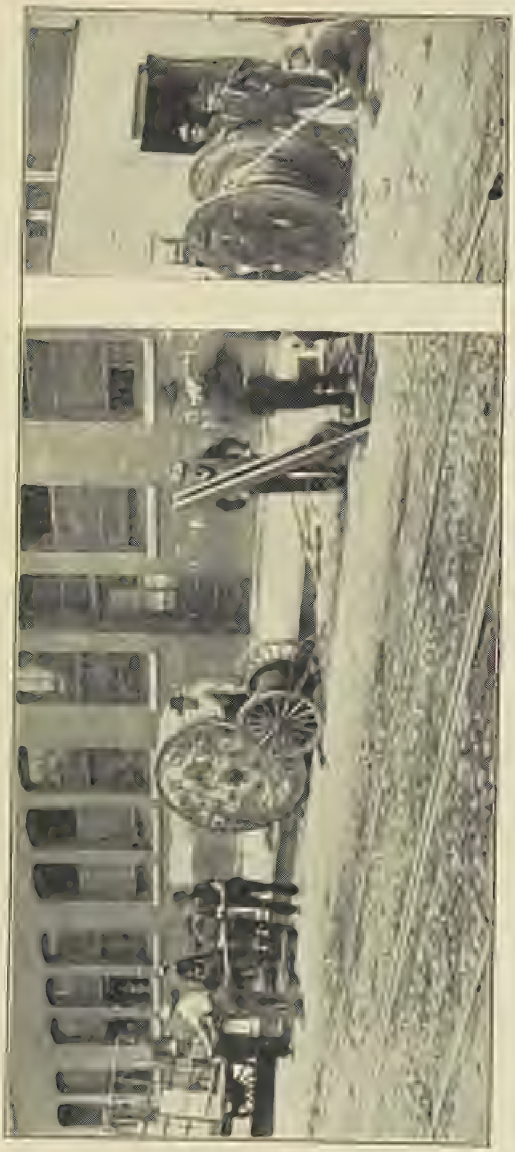


Fig. 159. Drawing in Cable by Capstan.

sufficient stock for training and making a fit with the adjoining length.

Where conditions permit two lengths are pulled in from opposite directions by one set up of the pulling truck. Where several cables are to be drawn into one duct they should be installed simultaneously by securing them to one line, as the duct cannot be utilized as fully as it should if it is attempted

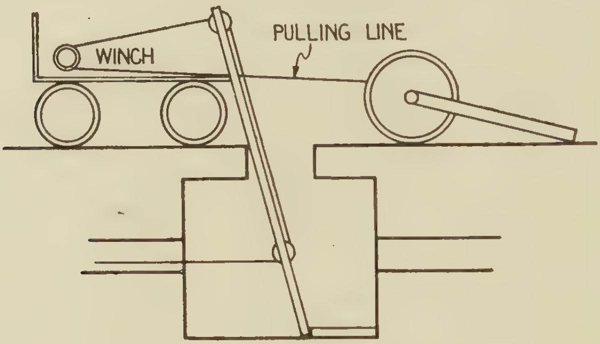


Fig. 160. Cable Pulling Rigging.

to pull them separately. Four single-conductor cables of any size up to # 0 A.W.G. can be drawn into a $3\frac{1}{2}$ inch duct without danger of injury.

Training Cables in Manholes. — The arrangement of cables in manholes should be intelligently planned to secure an orderly result and to protect the cables from the operating difficulties resulting from damaged sheaths and manhole fires.

Cables should be so trained as to allow sufficient movement to absorb the expansion and contraction resulting from variations in temperature and should be provided with suitable shields at the mouth of the duct to give a smooth surface upon which the sheath may travel.

The importance of this may be appreciated when it is

realized that a 500 foot length of cable installed at a temperature of 10° C. will expand several inches in coming up to a temperature of 70° C.

Flexibility is secured by introducing suitable bends, but these should be so arranged as to permit movement of the cable without seriously stressing the sheath of the cable and its supports.

The training of cables around corners must be done in such manner as to avoid injury to the insulation by sharp curves.

The minimum radius of bends should be from 6 to 10 times the diameter of the cable, the lower ratio applying to cables of larger diameters, and higher voltages. Much can be done in designing the manholes to give easy bends, by having no right angles at corners of manholes.

Cables are supported on racks hung from the side walls permitting ready installation or removal. The type of bracket shown in Fig. 161 is typical. The cable brackets are hung by detachable fastenings to vertical members secured to the walls. The bracket may be made for one, two, or three cables in a row at each level, the number being fixed by the number of cables which are to pass through the manhole.

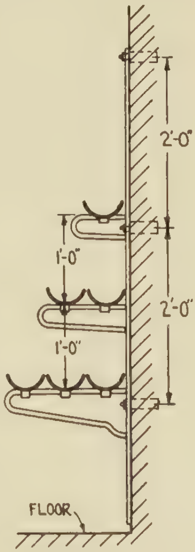


Fig. 161. Cable Racks.

The bracket in this particular type carries a detachable saddle on which the cable rests. All parts of the cable rack are galvanized.

Where junction boxes are present, through cables must be carried below them. Space can be conserved for this purpose by the use of types of boxes which permit cables to be brought in at the sides.

Cable Protection. — Where there are several cables with a large supply of energy the failure of a cable at any point within a manhole often results in an arc which may be sustained a sufficient time to seriously damage the sheath of other cables. In the case of low tension cables on an Edison system such an event has developed into a manhole fire which could be extinguished only by cutting off the supply of energy on all the cables going through the manhole causing a serious interruption of service.

It is, therefore, customary to cover cables in manholes with a fireproofing material of sufficient strength to withstand the heat of an arc from an adjacent cable. Various materials have been employed, such as asbestos tape, split tile, and cemented rope or wire mesh.

The most effective forms of fireproofing are those which consist of a cement covering held by a binder such as rope. Other forms are likely to break off in sections, thus exposing a larger part of the sheath than is desirable.

When rope and cement are used, the usual procedure is to wrap $\frac{1}{4}$ inch rope about the lead sheath in an open spiral having a pitch of about $\frac{5}{8}$ inch between turns. This is applied to the entire sheath from the mouth of the duct on one side to the other side of the manhole including the joint.

Cement plaster made up of two parts sand to one of cement is then applied to a thickness over the rope of about $\frac{1}{2}$ inch, or $\frac{3}{4}$ inch between turns. This is smoothed with a trowel to give a neat finish.

Jointing. — The various lengths of cable are joined at manholes to make a completed circuit, and the operation of jointing is very important, especially in the case of high voltage cables.

The jointer's work should be done only by men who have had special training and who have proven themselves to be

capable of doing their work conscientiously. In large organizations a careful record is kept of the joints made by each workman and his length of service as a jointer depends largely upon his record.

The work of jointing is made up of three groups of operations: (*a*) cutting the ends to the proper length and removing the sheath and insulation, (*b*) making the connection between conductors and applying the insulation, (*c*) wiping the lead sleeve over the joint and filling the voids with molten compound. Before trimming the ends the cable should be trained to its permanent position so that it will not have to be disturbed soon after the joint is completed.

The ends are then trimmed so that they come closely together and the lead is removed as far back as is necessary to give access to the conductors. If any evidence of moisture in the insulation is seen the cable should be cut farther back or if this is not possible, heat should be applied by a blowtorch to the sheath. The heat should be applied beginning near the duct entrance and working toward the end so as to drive out the moisture at the end. Moisture will be indicated by bubbling when the insulation is subjected to compound at 125° F. by dipping or pouring.

Care must be used and special tools are desirable for cutting the lead sheath, in such manner as not to injure the insulation.

Enough of the insulation is removed to provide the length of bare copper necessary for the connecting lug. Before soldering the lugs in place the lead sleeve which is to cover the joint must be slipped over one of the ends and pushed back out of the way until needed.

The lugs should have a carrying capacity equal to that of the cable to avoid local heating, and in the case of high voltage cables should be so shaped as to have no sharp corners or projections as these are points of high static stress. The

insulation is applied around the bared portions of the lug and conductor by wrappings of tape or by the application of tubes of insulating material. Taping is used in most cases for lower voltages and tubular shapes for the higher voltages where the size of the joint and the larger amount of taping required makes their use advantageous.

Various special forms have been devised and patented, the object usually being to provide shapes which can be applied after the lugs are soldered, thus shortening the length of lead sheath removed.

In applying insulation to high voltage joints it is important that moisture from the hands or elsewhere be carefully excluded and this is less difficult with prepared insulation than with taping.

After the insulation has been applied and secured in its permanent position the lead sleeve is slipped over the joint and its ends are joined to the sheath of the cable by a connection of wiped lead such as that used by plumbers in joining lead pipe.

The surfaces so joined must be scraped to remove all oxide of lead and protected by a flux of some material such as a tallow candle to insure a water tight connection.

The sleeve is provided with two holes, one for pouring hot compound into the sleeve and the other to vent the air and gases. Pouring is continued until the compound appears at the vent hole and bubbling ceases. The joint is allowed to cool and the void left by shrinkage is filled before the holes are sealed over with lead.

The various stages of a multiple conductor joint insulated by taping are illustrated in Fig. 162.

Various other forms of joints are required in addition to the simple splice above described.

In taking off taps from distribution cables a right angle connection is made resulting in a T joint. In some situations

it is easier to train such taps if they are taken off at an acute angle making a Y joint. In connecting three single conductor cables to a three conductor cable, as is sometimes done at a pole connection, the resulting figure is a "crab" joint.

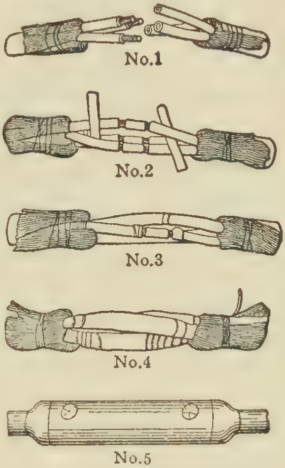


Fig. 162. Process of Making Joint.

Location of Cable Faults. — When a fault occurs in a working cable it is usually quite important that it be located and repaired very promptly, even though service may have been restored by use of reserve facilities. Means are, therefore, provided for making tests and locating trouble in cables with the least possible delay.

At cable terminal points, where tests are to be applied, the conductor is made accessible either by the use of disconnecting type potheads or by some form of switch blade disconnector to which connections may readily be made to the test apparatus and to ground.

The length of transmission and feeder cables is usually such that time is saved by making a loop test, from which the exact point can be calculated with fair accuracy.

The loop test is possible only where at least one of the conductors of the cable is continuous and not badly grounded.

The first test to be applied is, therefore, a continuity and ground test, which is made by the use of 110 volts direct-current, with a lamp or voltmeter as an indicator. One side of the test battery is connected to ground, and the other terminal is applied successively to each conductor of the cable.

If any conductor is fully grounded, the lamp will burn up

to full brilliance, or the voltmeter will indicate nearly full voltage.

If none of the conductors give a high reading of the voltmeter (90 or more at 110 volts), the cable insulation has not been left in such condition to conduct the test current. In such cases, a testing transformer applied to the cable to re-establish the arc for a short time will often improve the ground.

Having located the grounded conductor and a continuous conductor, the loop test is applied, using a slide wire bridge and a galvanometer, such as that shown in Fig. 163.

With the slide in mid-position, the galvanometer key is closed and the direction of the deflection is an indication of

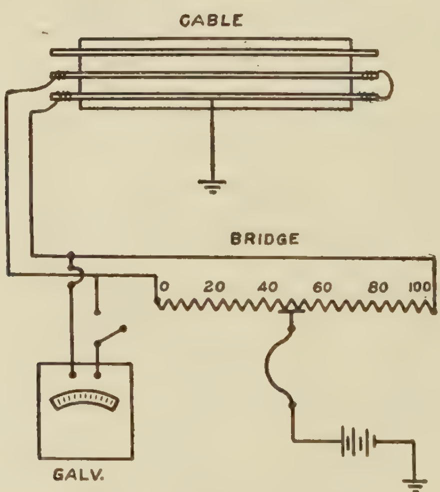


Fig. 163. Slide Wire Bridge.

the direction toward which the slide should be moved. The slide is then brought to a position at which the galvanometer is not deflected when the key is closed.

The scale is graduated from 0 to 100, and the reading is noted.

If the reading is a, 100 minus a is b, the distance to the fault by way of the far end and back is c, and the direct distance to the fault is x, we have the ratio $\frac{a}{b} = \frac{c}{x}$. $b = 100 - a$, and $c = 2L - x$, if L is the length of the line.

$$\text{Then } \frac{a}{100 - a} = \frac{2L - x}{x} \text{ and } x = \frac{2L(100 - a)}{100}.$$

If the scale reading $a = 80$ and $L = 30{,}000$ feet, the distance to the fault is $x = \frac{2 \times 30{,}000\,(100 - 80)}{100} = 12{,}000$ ft.

The scale reading should be checked by reversing the leads, in order to eliminate possible distortion caused by stray currents. If there should be a material difference between the scale readings, as taken with direct and reversed connections, the loop test cannot be depended upon as an indicator of distance.

It is then necessary to resort to some form of tracing current device, operating somewhat as follows:

An intermittently applied source of potential from an alternating-current system is connected from ground to the faulty conductor of the cable. When a listening coil and telephone receiver are applied to the cable, between the test point and the fault, the intermittent potential is heard in the receiver.

Proceeding to the mid-point of the circuit, it is determined whether the ground is beyond or nearer the test point. This is again halved and the location found by trial.

The signal is absent or much reduced on the far side of the fault.

This method usually requires more time than the loop test, if the line is more than 2 miles long.

The exact location of the fault. when the point indicated by the loop test is approached. is often made apparent by smoke

emerging from a manhole, by the odor of burning insulation or by residents of the neighborhood who have seen evidence of a disturbance.

However, there are enough cases where this is not true, so that it is found advisable to apply the tracing current apparatus in all cases while the work of location is proceeding. This insures an exact location in the minimum time after reaching the locality.

The equipment for making cable tests of this kind should be assembled in conveniently portable form, so that it can be taken from station to station if necessary. Each important station is, however, usually provided with its own equipment.

Pole Terminals. — In primary distributing systems in which part of the lines are underground, there are connections made between underground and overhead lines. It is usual to run feeders and important mains underground for some distance from the station in large cities, connecting them to the overhead lines in the more scattered areas.

Where alley distribution is general the main lines are placed underground on streets and the local distributing taps taken off to overhead lines in alleys. In other locations lines must be carried underground across a boulevard, railroad or stream. This class of distribution was for many years very troublesome because of the difficulty of properly caring for the cable ends which are brought up the pole to the overhead lines.

The problem was quite satisfactorily solved by the development of a type of cable terminal embodying porcelain sleeves into which the conductor of the lead covered cable was brought for attachment to the overhead conductor. The authors developed the first of this type of cable terminal in 1905 to meet conditions which were very troublesome in connection with single-conductor cable in Chicago. The porcelain sleeve is placed about the end of the cable and

equipped with a slip joint by which the cable conductor can readily be connected to or disconnected from the overhead conductor, as shown in Fig. 164. The tube is covered at the top by a porcelain cap which serves the double purpose of protecting the tube from the weather and holding one of the connecting metals. The tube is filled with a suitable insulating compound to protect the cable insulation from moisture and the top of the cap is well taped and painted so that no rain can enter around the overhead wire. An installation of these appears in Fig. 165.

Fig. 164. Disconnecting Pothead.

The factor of safety was so greatly increased by the greater separation made possible by this construction that the trouble from puncture by lightning was entirely eliminated and the cable terminal became as reliable as any other part of the distributing system.

This type of cable terminal was readily adapted to use with multiple-conductor cables by mounting the porcelain tubes in the lid of a metal pot within which the conductors are separated and protected from moisture by a filling of molten insulating compound, as illustrated in Fig. 166.

The detachable cap provides means of disconnecting each of the conductors of the cable separately when necessary for testing and fault location work.

A variety of types have been developed to meet the various situations in which potheads are placed and the different voltages in common use.

In the case of 3-conductor cables, the pot may be flat, triangular, or circular. The flat arrangement is usually preferred where sidewise space is more easily had than depth, as on the side of a pole. The end tubes are usually set in the

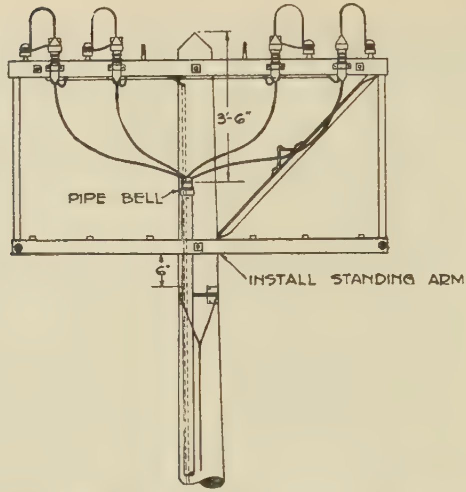


Fig. 165. Installation of Single Conductor Potheads.

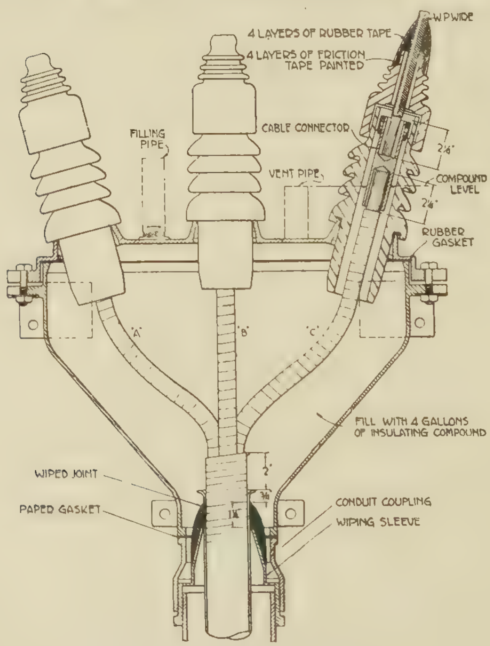


Fig. 166. Pothead Assembly.

lid at an angle, as in Fig. 166, to increase the working space between the overhead-conductors at the point where they connect to the caps. This is also done with a triangular arrangement of the tubes for the same reason.

The triangular or circular pot is used where space is ample and a little greater spacing is desired between the caps. This is usually the case at pressures above 15,000 volts.

At pressures above 35,000 volts, it is easier to secure the necessary separation at the caps by bringing single-conductor

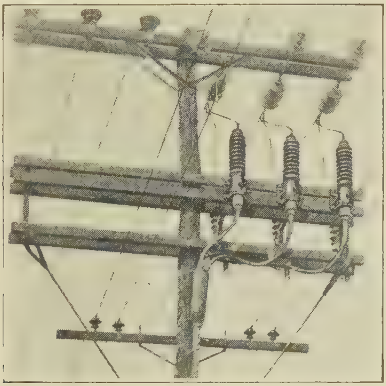


Fig. 167. High Voltage Potheads.

cables up to a similar type of potheads, mounted as in Fig. 167, at the desired distance from each other.

Where 6 to 8 conductors are brought out, as in series lighting installations at the substation end, the pot is usually in rectangular form, 2×3 or 2×4 tubes being carried in the lid. See Fig. 10.

The cable is brought into the pot through a wiped sleeve joint, or through some form of stuffing box which holds the filling compound. The stuffing box is preferable where experienced jointers are not available to make wiped joints.

The relative position of the cable entrance in the pot is varied to suit the conditions of installation.

The more common form is that of Fig. 166, used where the cable enters directly from below.

Where the cable enters from the side, at a level near that of the pothead, the side entrance type is useful. This avoids a sharp bend in the cable sheath, as it is made inside the pot.

The use made of this type in connecting to a substation transformer, out-of-doors, is well illustrated in Fig. 168.

On a pole, it is often desirable to place the pothead on crossarms at one side to avoid interference with climbing space.

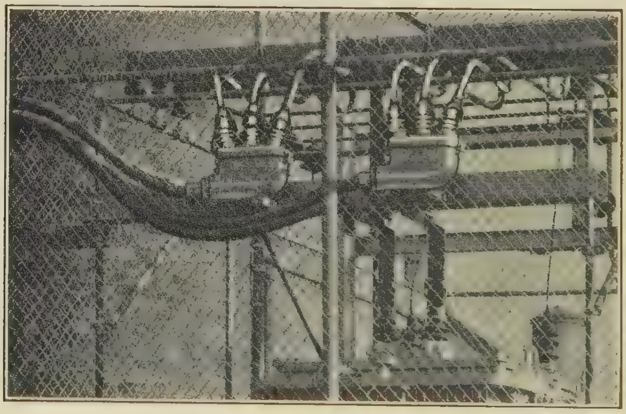


Fig. 168. Side Entrance Potheads.

The side entrance type has found wide application on 4000-volt 4-wire systems. Two (2) of them may be readily mounted on a pole in the manner indicated in Fig. 169 without interfering with access to other equipment on the pole and, yet, within easy reach for operation of the disconnecting caps whenever necessary.

The current-carrying contacts of disconnecting potheads vary in design according to their intended use and the volume of current which they are intended to carry.

Slip contacts with spring parts to insure proper conductivity are the simplest in operation, and are used where disconnection is likely to occur periodically. For current ratings over 500

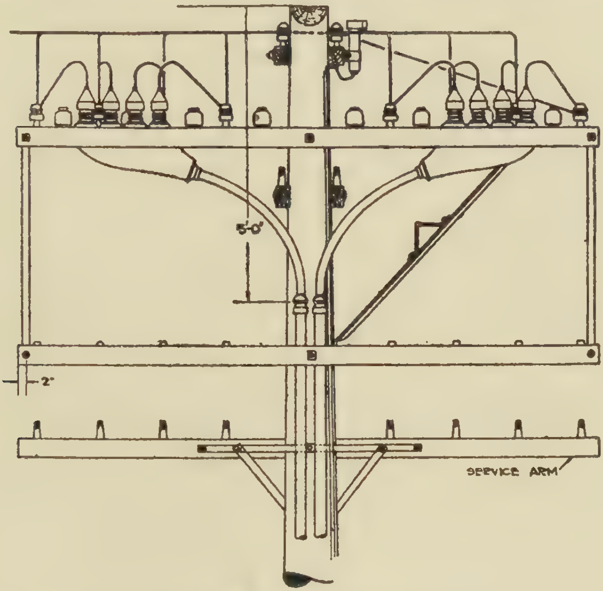


Fig. 169. Pole Top Pothead Installation.

amperes, screwed contacts or bolted lugs above the cap have been used to some extent.

One type of screw contact is operated by an intermediate porcelain sleeve, without the use of tools and without the necessity of touching any live parts.

One type of bolted lug connection is shown in Fig. 170. It is used chiefly where the necessity of disconnecting is very infrequent, as in an installation where other disconnectors are provided for regular operating purposes.

Station Terminals. — Potheads for cable terminals within stations are similar to outside potheads, as regards the shape

of pots, cable entrances, and disconnecting features. However, where the non-disconnecting type meets the requirements, the porcelain tubes are of a different design and the weather caps are omitted. A common type used within stations is that shown in Fig. 171.

The connection from the cable conductor to the bus conductor is made through a soldered lug within the pot, or in some cases the insulated conductor is extended through the

Fig. 170. Pothead, Connection Bolted.

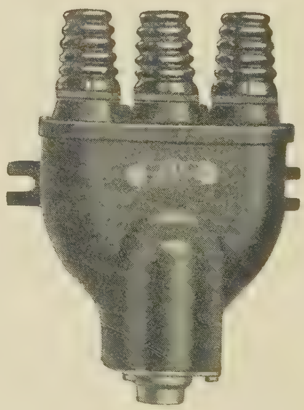


Fig. 171. Inside Type Pothead.

tubes in sufficient length to be connected directly to a bus lug. In such cases, the paper outside the pothead should be wrapped with linotape for protection from moisture.

In a station there are often situations requiring the use of angle shaped potheads to admit cables approaching from either side, front or rear, and even in some cases from the top.

Some of the various types designed to meet these conditions are seen in Fig. 172.

Transformer Installations. — Underground transformer installations are placed in manholes, or in vaults prepared especially for them under sidewalks or within the basement of a building.

When placed in street manholes, the transformer and equipment are usually subject to occasional flooding due to overflowing sewers and must, therefore, be submersion proof.

The transformers are, therefore, provided with sleeve connections, which are wiped to the cable sheath, and the covers are made water tight.

Fuse boxes should be similarly equipped.

In sub-sidewalk spaces, and in basements, the vault is usually not subject to flooding. The cables bringing the

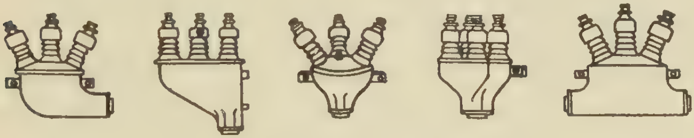


Fig. 172. Various Shapes of Potheads.

primary supply and its reserve connection to such vaults are terminated in disconnecting potheads, or a disconnecting junction box.

When potheads are used at voltages up to 5000 no other disconnector is required for the purpose of isolating equipment for repair work. At higher voltages, it is usually considered preferable to provide a disconnecting box and an oil-switch for primary control.

Where the character of the installation is such as to necessitate a primary reserve supply, facilities are provided for promptly transferring the transformers from the normal supply to the reserve supply.

At the usual distributing voltages this can often be accomplished by mounting disconnecting potheads in such manner that the caps connected to the primary side of the transformers

can be transferred to the tubes of the reserve supply. The reserve supply tubes are normally covered by dummy caps to protect them from dust and corrosion. Such an installation is seen in Fig. 173.

In the case of such institutions as hospitals, hotels, and theatres, the emergency switching equipment is often arranged to be controlled by an authorized person on the premises, in order to shorten the time of an interruption. In such cases, an oil-switch is employed and the control handle

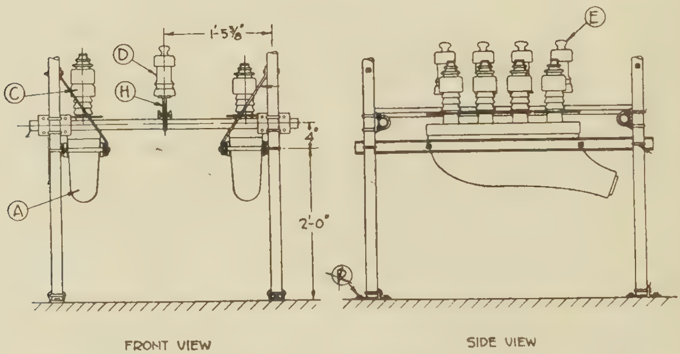


Fig. 173. Disconnecting Potheads used as Transfer Switch.

is brought outside the vault by suitable connecting levers and rods.

Automatic throw-over by means of no-voltage relay control has also been used to a limited extent in such service. The relay is arranged to open the normal supply and to close the reserve supply when the normal supply voltage disappears. When service is resumed on the normal supply, the switch automatically reverts to the normal position.

Such arrangements are, of course, permissible only where an ample reserve feeder capacity is maintained.

The secondary connections of the transformer are fused when they are a part of an interconnected secondary network.

In such cases, the fuses are placed in a cable junction box of the low-tension type.

The arrangement of transformers and equipment in a vault should be so planned as to give access for repairs and for the replacement of a damaged unit, with as much facility as the situation permits.

In manholes, the connections are of lead covered cable and should be trained on side walls where they will not be damaged by normal use of the manhole in operating the equipment.

In vaults which are not likely to be invaded by water, the primary connections from pothead to fuses and transformers,

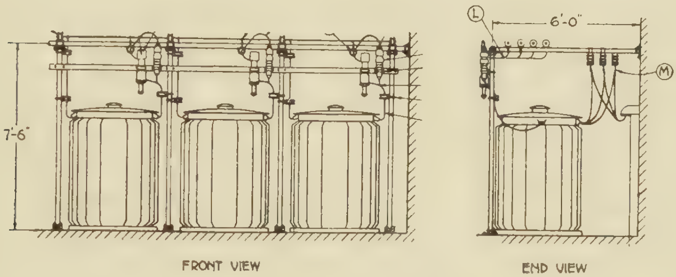


Fig. 174. Transformer Vault.

and the secondary connections may be carried on insulators supported by a suitable pipe framework to give proper clearance from the floor for working spaces.

Such an installation appears in Fig. 174.

The heat liberated in a transformer vault must be radiated to the air and to surrounding walls. In the larger vaults the circulation of air must be relied upon to carry away the major part of the heat, though, in the largest industrial vaults, water-cooled transformers are sometimes used.

Street or sidewalk vaults are cooled, where conditions permit, by the erection of a ventilating stack at the curb or building line. Such stacks should have capacity to discharge

the cubic contents of the vault in about 2 minutes, when there are 2 cubic feet of air per kv-a.

Cable Disconnectors. — Primary distribution cables must be arranged to be disconnected for repairs or construction work, since it is not feasible to do jointing with the cable alive.

On a ring feeder this is readily accomplished without interruption of service by providing disconnectors on each side of the customer's loop at the vault. A new loop may then

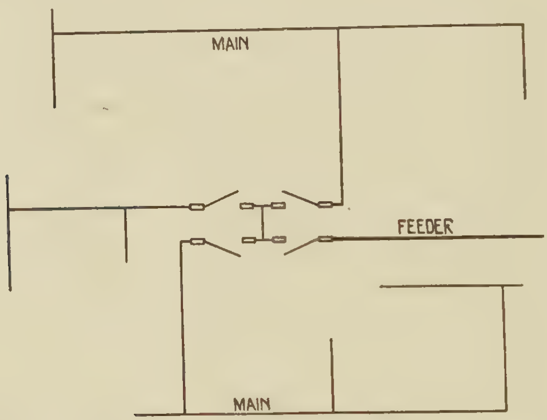


Fig. 175. Arrangement of Disconnectors at Feeder End.

be cut in to any section, or a fault may be repaired without interrupting service to any of the users of energy from the ring.

Where distribution is carried out through centers of distribution, from which radial cable mains are supplied, there should be a disconnector on each of the cable mains, as indicated diagrammatically in Fig. 175.

This is often accomplished by the use of a multiple-way junction box, such as that shown in Fig. 176. In this box

the feeder is brought in through one set of disconnectors and each main passes out through disconnectors.

In case the feeder itself fails, the mains may be supplied through emergency connections at other points after the feeder disconnectors have been opened.

In a similar way either of the mains may be isolated in case of failure, or when additional branches or transformers are being connected to the line.

In case the primary main is extensive, it should be further provided with sectionalizing disconnectors to reduce the extent of the area affected by a fault in the cable. This may be done through a disconnecting junction box, or by 2 sets of potheads with jumpers across the caps. The potheads are used on smaller mains, where their operation is not frequent. Their use for such purposes is not prevented by occasional flooding, as the cap, when well taped at the top, forms an air bell which does not permit water to come near enough to live parts to cause failure.

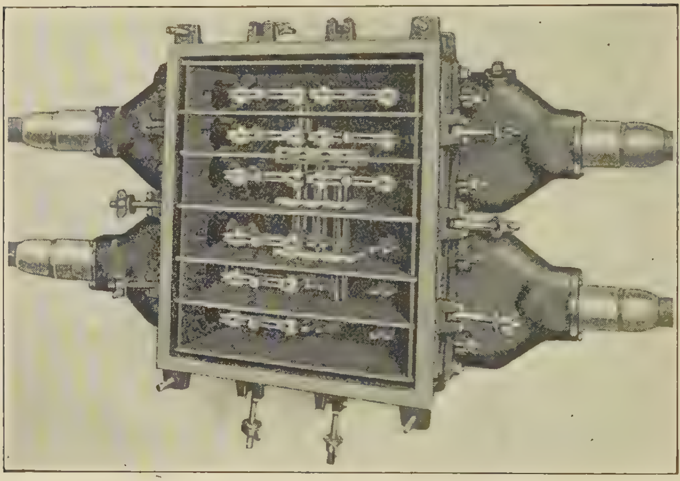
Installations of this kind have been submerged while alive at 4000 volts for upward of 12 hours without causing trouble.

Where maintenance men are chiefly overhead linemen, it is found preferable to loop the main up a pole where the disconnectors are easily accessible to a man working alone in tracing the location of trouble.

Secondary mains, forming a part of an interconnected network, are sectionalized by fused junction boxes at all points of intersection. The fuses thus serve as isolators of each section of main between junctions, and limit the area affected by a cable fault.

In case it should be necessary to isolate a section for construction or maintenance work, it is readily accomplished by removing fuses.

Such a box as that seen in Fig. 177 serves this purpose,



176. Primary Disconnective Box.

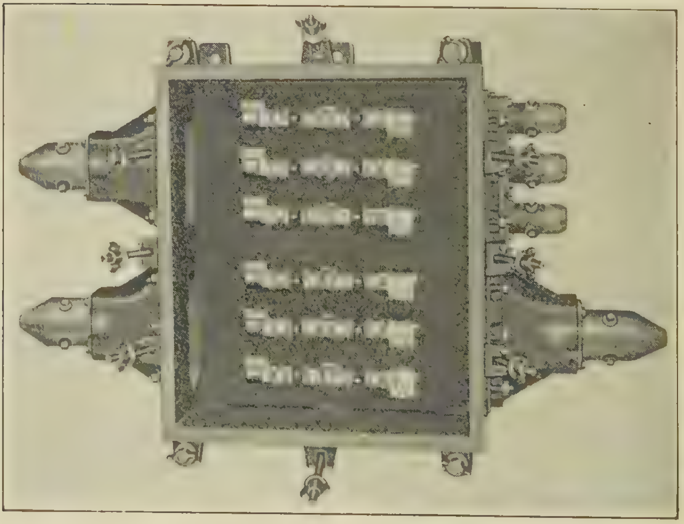


Fig. 177. Secondary Fuse Box.

where a 4-way connection is made. 2-way, 6-way, or larger combinations are made in a similar way.

Where no fuses are required, as for service branches to separate buildings, the box is a simple disconnecting device, such as that in Fig. 178. The branches are disconnected by

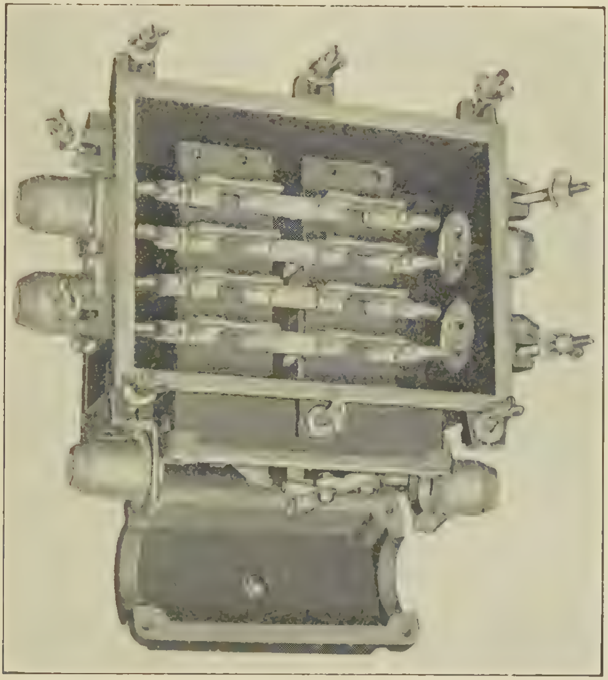


Fig. 178. Secondary Disconnecting Box.

withdrawing the switch blade connector. In the particular type shown, the lower part of the box is provided with a split collar, by which the main can be tapped into the box without cutting the cable conductors, after the insulation has been removed.

CHAPTER XIV

DISTRIBUTION ECONOMICS

There are various problems involved in the engineering design of a distribution system which have an economic aspect in that they have a direct relation to the success of the property as a business enterprise. Distributing feeders form a considerable part of the plant investment and their design affects the generating plant and the efficiency of operation.

The distributing voltage being fixed by practical considerations of safety and continuity of service, it is the usual practice in large systems to adopt certain standard feeder capacities which are made as large as is practical. With transmission lines, when a standard voltage has been established, it is usual to adopt certain line capacities beyond which it is not desirable to go. Thus the problem usually resolves itself into the selection of the proper size of conductor for the unit of load adopted.

Economical Size of Conductor. — In the selection of the size of a conductor for a feeder or transmission line the energy loss tends to diminish as the size of the conductor is increased, and *vice versa*. The generating capacity required to supply the energy loss also decreases as the size of the conductor is increased.

Hence there is a point at which the sum of the fixed charges on conductor, fixed charges on generating capacity, and the value of energy loss is a minimum. The size of the conductor with which this condition of minimum annual cost is realized is that which it is the most economical to employ.

The fixed charges are composed of interest on the capital, depreciation of the physical property, taxes and insurance.

The energy loss is computed at the cost of energy as delivered at the switch-board from which the circuit is supplied.

In calculating interest the investment figure should include the cost of the conductor with its insulation and any other expense which is proportional to its cross-section.

Interest should be figured at the current rates for the use of money for public service utilities.

Depreciation. — The depreciation of distribution lines is determined by their useful life and the net salvage value realized at the time of replacement, after deducting the cost of removal.

The weatherproof insulation, commonly used for overhead conductors, has an average working life of about 12 to 15 years. The copper, which in sizes used for feeders constitutes about 83 per cent of the total weight, is salvaged at a junk price, which is normally about 2¢ per pound below the cost of new copper, and the labor cost of removal is also about 2¢ per pound of copper removed, making a total loss of about 25 per cent, when copper costs 15¢ per pound.

The 17 per cent of original weight represented by the insulation is entirely depreciated at the end of 12 to 15 years.

The total depreciation of weatherproof wire is, therefore, $25 + 17 = 42$ per cent, or at the rate of 3 per cent per year for 14 years.

The life of paper, or rubber-insulated, lead covered cables depends largely upon the temperatures at which they have been operated, but assuming that reasonable care is exercised to prevent long continued over-heating, it has been found that such insulation may be serviceable for upwards of 20 years. However, the life of cables is appreciably shortened in growing systems by withdrawal of cables, as is necessary to meet

load conditions. Cable so withdrawn after years of service is often damaged in handling and parts of it are junked.

The scrap value of lead-covered cables of the larger sizes is not so high as for overhead wires of the larger sizes.

In view of these conditions an allowance of 4 per cent for cables of over 200,000 circular mils and 5 per cent for smaller sizes seems reasonable.

For generating station equipment, where obsolescence is a considerable factor, it is usually considered that 4 to 5 per cent is a fair rate of depreciation.

Total Fixed Charges. — The total fixed charges include interest and taxes, as well as depreciation.

In public utility financing the cost of capital averages about 6.5 per cent. Taxes average 1.5 per cent.

For overhead lines the total fixed charges may, for purposes of illustration, be taken as $6.5 + 1.5 + 3.0 = 11$ per cent.

For cables the total fixed charges may likewise be taken as $6.5 + 1.5 + 4.0 = 12$ per cent.

For generating stations the total is $6.5 + 1.5 + 5 = 13.0$ per cent.

These values will be used for purposes of illustration in the examples following.

General Equation for Minimum Annual Cost. — The total annual cost of an electric circuit may be expressed by a general equation as follows:

$$Y = \frac{a}{R} + bC^2R + cC^2R.$$

In this expression $\frac{a}{R}$ represents the fixed charges on the conductors and their insulation, if any, a being a constant which may be determined for bare, weatherproof or lead covered

conductors with sufficient accuracy for this purpose. This portion of the cost is proportional to the conductivity, $\frac{1}{R}$, of the conductor. bC^2R represents the fixed charges on the generating station capacity required to supply the C^2R loss, b being a constant which is fixed by the type of generating plant involved. cC^2R is the value of the energy loss on the circuit per annum, in which c is a constant depending upon the unit cost of producing energy and the character of the load carried by the circuit.

In each of these three elements of cost R is the resistance per 1000 ft. of the conductors of the circuit.

The value of Y, the total annual cost, is a minimum by the rule of calculus when $\frac{dy}{dR} = 0$.

$$\frac{dy}{dR} = \frac{(b + c)C^2R^2 - a}{R^2}.$$

When $\frac{dy}{dR} = 0$, $(b + c)C^2R^2 - a = 0$ and $C^2R^2 = \frac{a}{b + c}$,

$$CR = \sqrt{\frac{a}{b + c}},$$

from which it is known what value of R and hence what size of conductor is most economical for any known value of C, the current carried by the circuit at the time of maximum load of the year.

The proper size of conductor to use as a standard feeder may be determined by this formula. Or, if a standard size of feeder conductor is adopted, the most economical maximum load for the standard feeder may be found.

It is assumed that the voltage has been established and the formula is therefore applicable to conditions already existing. The length of the feeder and the working voltage are

not factors in the problem since the economic balance is determined solely by the values of C and R for a given set of working conditions.

Fixed Charges on Conductors. — The value of the conductors of a circuit is directly proportional to their size and inversely to their resistance when the conductors are bare or insulated for overhead construction. With lead-sheathed cable the cost is nearly proportional, when a few adjacent sizes are considered in comparison with each other.

For bare wire the product of weight per 1000 feet W by resistance per 1000 feet for all sizes is $WR = 32$, while with weatherproof insulation it is $WR = 38$ for the sizes # 4 to # 0, or 36 for sizes from 2/0 to 350,000 c.m. The value of 1000 feet of conductor at 15 cents per pound is therefore .15 W dollars. Hence, when $W = \frac{38}{R}$, the cost per conductor per thousand feet is $\frac{.15 \times 38}{R}$ dollars.

With fixed charges at 11 per cent this element of annual cost is $\frac{a}{R} = \frac{.11 \times .15 \times 38}{R} = \frac{.627}{R}$ dollars per year per 1000 ft. of conductor.

With underground conductors the value of insulation and lead sheath is a large proportion of the cost of the smaller sizes of cable, and a change in the size of the copper conductor does not make a proportionate change in the cost of the cable.

The resistance per 1000 c.m. per 1000 feet of copper at ordinary temperatures is about 10.4 ohms. If M is the number of thousands of circular mils, the cost per 1000 ft. of a single-conductor cable is M times the cost per 1000 circular mils. $M = \frac{10.4}{R}$ and the cost of the cable is $\frac{10.4 \times P}{R}$, where P is the cost per 1000 circular mils and per thousand feet, in dollars.

The following table gives the cost per 1000 circular mils of various sizes of single- and three-conductor lead-sheathed cables for ordinary distributing voltages.

Cir. Mils 1000 s	Cost per 1000 Ft. per 1000 Circ. Mils		
	Single Cond. .6 kv.	Three Conductor	
		13 kv.	.6 kv.
105	1.90	2.15	1.61
133	1.80	2.05	1.52
166	1.67	1.88	1.44
212	1.53	1.73	1.36
250	1.40	1.60	1.30
300	1.35	1.50	1.25
350	1.28	1.43	1.20
500	1.20	1.30	1.10
750	1.13	....	....
1000	1.06	....	....
1500	1.02	....	....

For single-conductor low-tension cable the value of P in the table is $1.20 for cables of 500,000 c.m. and the value of each conductor is $\frac{10.4 \times 1.2}{R} = \frac{12.48}{R}$ per 1000 feet. With fixed charges assumed at 12 per cent, the annual conductor cost per 1000 feet is $\frac{a}{R} = \frac{.12 \times 12.48}{R} = \frac{1.46}{R}$ per conductor. In applying this, if the most economical size proves to be below or above the sizes for which the cost was assumed, the figure should be corrected, using the price per 1000 c.m. corresponding to the size which seems on the first approximation to be the most economical. In this way the most economical size may be determined on the second determination if the first seems to have been based on false premises.

With three-conductor cables the cost per 1000 circular mils

in the table is based on the total cross-section of the three conductors.

If the cable is operated on a 3-phase load balanced, these values may be used directly with the corresponding values of C and R for demand charges and energy losses.

However, on a 3-wire Edison circuit, with neutral of the same size as the outers, the cost of conductor must be increased one-half, and $\frac{a}{R}$ becomes $\frac{1.5\,a}{R}$. This makes the cost of wire comparable with demand and energy costs, which are for one current-carrying conductor.

In the case of a 4-wire, 3-phase circuit the factor is 1.33 and the cost is $\frac{1.33\,a}{R}$.

Fixed Charges on Generating Equipment. — In estimating the value of generating capacity required to deliver the loss at maximum load, the cost of boilers, prime movers and generators should be included, as all are affected. This cost varies greatly in different plants, depending upon the size and character of the equipment. In turbine plants of 10,000 kw. and upward the investment exclusive of real estate is from \$110 to \$140 per kw.

The station capacity required to supply the energy loss at the time of the annual maximum load is $\frac{C^2R}{1000}$ kw. per 1000 feet of conductor.

The value of station capacity required to supply the loss on a feeder when the cost is \$120 per kilowatt is $\frac{120 \times C^2R}{1000}$ and the fixed charges at 13 per cent are $bR = .13 \times .12\,C^2R = .0156\,C^2R$ dollars per conductor.

Energy Loss. — The loss of energy on a circuit during a year is dependent upon the variation of load from hour to hour and from day to day throughout the year.

The variation from hour to hour in general distribution work changes from day to day, depending upon the habits of the people who use the electricity and from season to season as the length of the daylight hours changes. In Fig. 179 typical average curves are shown for a lighting feeder which carries a small amount of day power load, for the months of March, June, September and December. The energy loss

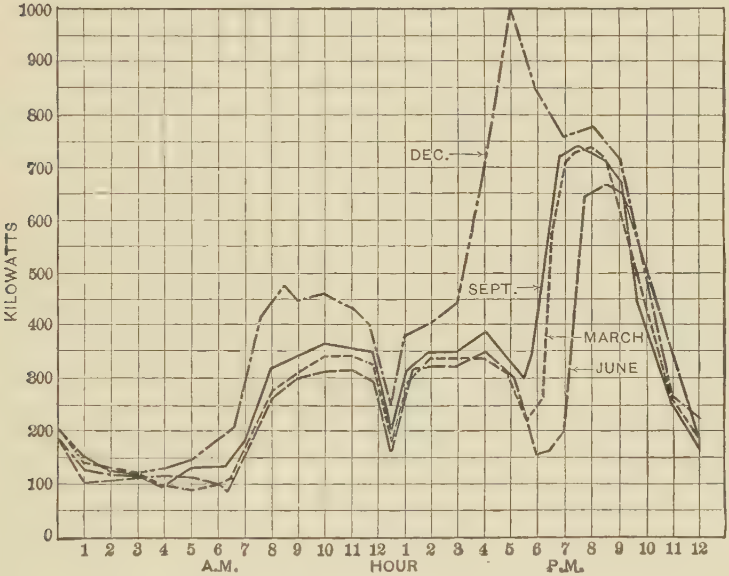


Fig. 179. Lighting Load Diagrams.

will evidently be different on this feeder each month in the year, being least during the summer months and most during December. Figure 180 shows similar curves for a power circuit which carries a small amount of lighting during the evenings. This curve is also similar to that which prevails on a transmission system where a considerable amount of power is supplied to industrial concerns during the day.

Loss Factor. — The annual loss on a circuit carrying load of given characteristics may be computed with sufficient accuracy for practical purposes as follows:

Taking a curve representing the load in amperes on an average day in March, assume a resistance of one ohm and

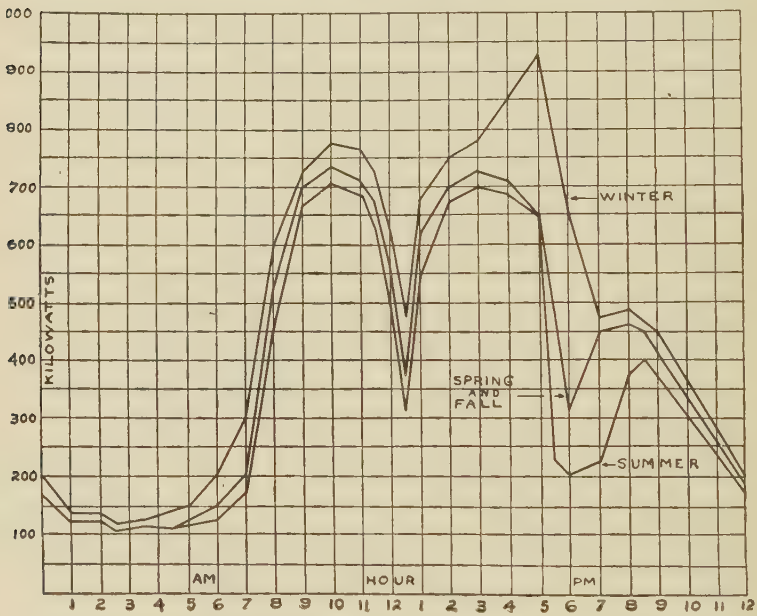


Fig. 180. Power Load Diagrams.

compute the value of C^2R for each hour of the day. The sum of these 24 quantities divided by 1000 is proportional to the loss in kilowatt hours on an average day in March. Repeat this operation for the June, September and December curves. Multiply the sum of the values from the four curves by 91, the number of days in each quarter of the year. This product is proportional to the annual loss in kilowatt hours on any feeder carrying a load having the general characteristics of the load curves used.

The ratio of the loss as thus calculated to the value of the loss if the feeder had carried the maximum load of the year may be called the *loss factor*, just as the ratio of the actual output for the year to the possible output at the rate of the maximum load is called the *load factor* of a circuit.

For instance, if a circuit carries a maximum load of 100 kw. and delivers an amount of energy equivalent to a load of 100 kw. during 2190 hours per year, the load factor of the feeder for the year is $\frac{2190}{24 \times 365} = 25$ per cent.

Similarly if the total energy *loss* on a circuit for a year is equivalent to the loss at maximum load multiplied by 2190, the loss factor for the feeder year is 25 per cent.

If C is the current at the annual maximum load and R is the resistance per 1000 feet of conductor, the loss at the time of the annual maximum load is C^2R.

If the loss factor of the feeder is 20 per cent, the annual loss is

$$\frac{C^2R \times .2 \times 365 \times 24}{1000} = 1.752\, C^2R.$$

The loss factor for a load having the characteristics illustrated in Fig. 166 is 16 per cent, while that of the curves in Fig. 167 is 28 per cent.

In a constant-current circuit the loss factor is the ratio of the number of hours the circuit is operated during the year to the total number of hours in the year. It is usually the same as the load factor of the circuit.

Calculation of Loss. — With the character of the load curve known, the loss factor may be determined in the manner described and the annual loss of energy calculated in terms of R, the resistance per 1000 feet of conductor.

The loss at the time of the annual maximum load being C^2R, the annual loss in kilowatt hours is equivalent to the

product of the maximum load loss by the number of hours in the year and by the loss factor, F.

There being 8760 hours in a year, this is $\frac{C^2R \times 8760 \times F}{1000}$ kilowatt hours. The loss $= 1.4\, C^2R$ kw.-hours when the loss factor is 16 per cent. The value of this energy may be computed at the cost of fuel and supplies, as no extra labor is required to deliver it, as a rule. The cost can therefore be taken at about 1 cent in small plants, .70 cent in larger plants and .5 cent in turbine plants.

At 1 cent per kilowatt hour the value of the energy loss per conductor is $C^2R = .014\ C^2R$ dollar per year at 16 per cent loss factor, or. 0245 C^2R at 28 per cent loss factor.

Summary of Annual Costs. — The total annual cost is the sum of the three quantities $\frac{a}{R}$, bC^2R and cC^2R. For weatherproof wire with station capacity at $120 per kilowatt, a loss factor of 16 per cent and energy at 1 cent a kilowatt hour, the annual cost per 1000 feet of wire is

$$\frac{a}{R} + bC^2R + cC^2R = \frac{.627}{R} + .0156\, C^2R + .014\, C^2R$$

$$= \frac{.627}{R} + .0296\, C^2R.$$

The value of these three elements will be a minimum for given values of C, the current at the time of the annual maximum load,

when $$C^2R^2 = \frac{a}{b+c} = \frac{.627}{.0296} = 21.18.$$

$CR = \sqrt{21.18} = 4.6$ and $R = \frac{4.6}{C}$ when the most economical size is used. For instance, if $C = 100$ amperes, $R = .046$ ohm, which is about the resistance per 1000 feet of 4/0 cable.

This apples only to a circuit in which each conductor carries current normally. With a three-wire Edison feeder with neutral half the size of the outers the amount of copper is increased 25 per cent, without increase in b and c, and $\frac{a}{R} = \frac{.627 \times 1.25}{R} = \frac{.783}{R}$. Hence $CR = \sqrt{\frac{.783}{.0296}} = 5.14$ for the outer conductors of a three-wire circuit.

Similarly with a four-wire three-phase feeder with neutral the same size as the phase wires the amount of copper is increased 33 per cent and $\frac{a}{R} = \frac{.627 \times 1.33}{R} = \frac{.836}{R}$, whence $CR = \sqrt{\frac{.836}{.0296}} = 5.31$.

These values involve a current density of about .5 ampere per 1000 circular mils, which is much lower than is commonly found. This is due perhaps to the fact that the expenditure of funds for line conductors is plainly evident, while the value of the generating capacity which is tied up by cutting the size of the conductor to a minimum is not so apparent.

Practical Illustrations. — For illustration, a few cases which are common in practice for both larger and smaller systems are carried through herewith.

Case I. — Weatherproof wire at 15 cents a pound, generating capacity at $120 a kilowatt, energy .5 cent per kilowatt hour, and load curve such that the loss factor is 18 per cent. Under these conditions

$$\frac{a}{R} = \frac{38 \times .15 \times .11}{R} = \frac{.627}{R}, \quad bC^2R = \frac{120 \times .13}{1000} C^2R = .0156\, C^2R,$$

$$cC^2R = \frac{.005 \times 8760 \times .18\, C^2R}{1000} = .0079\, C^2R.$$

$CR = \sqrt{\frac{.627}{.0235}} = 5.16$ per conductor which carries a current C.

At $C = 200$ amperes, $R = .0258$ ohm.

Case II. Underground cables at values given in the table, generating capacity at \$120 per kilowatt, energy at .5 cent per kilowatt hour, and loss factor at 25 per cent. With single-conductor low-tension cable, 1,000,000 c.m., the cost per 1000 c.m. averages \$1.06.

Hence $$\frac{a}{R} = \frac{.12 \times 10.4 \times 1.06}{R} = \frac{1.32}{R},$$

$$bC^2R = \frac{120 \times .13\, C^2R}{1000} = .0156\, C^2R,$$

$$cC^2R = \frac{.005 \times 8760 \times .25\, C^2R}{1000} = .0109\, C^2R,$$

and $$CR = \sqrt{\frac{1.32}{.0265}} = 7.1 \text{ per conductor.}$$

With 700 amperes $R = \frac{7.10}{700} = .0101$, which is about the resistance per 1000 ft. of 1,000,000 c.m. cable.

Case III. Three-conductor cables, generating capacity at \$120 per kilowatt, energy at .5 cent per kilowatt hour and loss factor at 25 per cent, 13,000 volts three phase, 200 amperes. The cost of cable is \$1.60 per thousand circular mils.

$$\frac{a}{R} = \frac{.12 \times 1.6 \times 10.4}{R} = \frac{2.00}{R} \text{ per conductor,}$$

$$C^2R(b + c) = .0265\, C^2R \text{ per conductor,}$$

$$CR = \sqrt{\frac{2.00}{.0265}} = 8.5, \quad R = \frac{8.5}{200} = .0425,$$

when C is 200 amperes, and this value is nearest the resistance of 250,000 c.m. cable.

Economics of Secondary Mains, Interconnected. — With the secondary mains of adjacent transformers interconnected, the size of conductor necessary to distribute the load with the usual limit of voltage drop from the transformer to the

mid-point between transformers must be increased as the spacing between transformers is increased.

For a given load density, such as 50 kv-a. per 1000 feet of main, the size of transformers and the number required per 1000 feet also vary with the spacing between transformers.

As more and smaller transformers are provided, a smaller size of conductor may be used, and vice versa.

Smaller transformers cost more per kv-a., and have higher

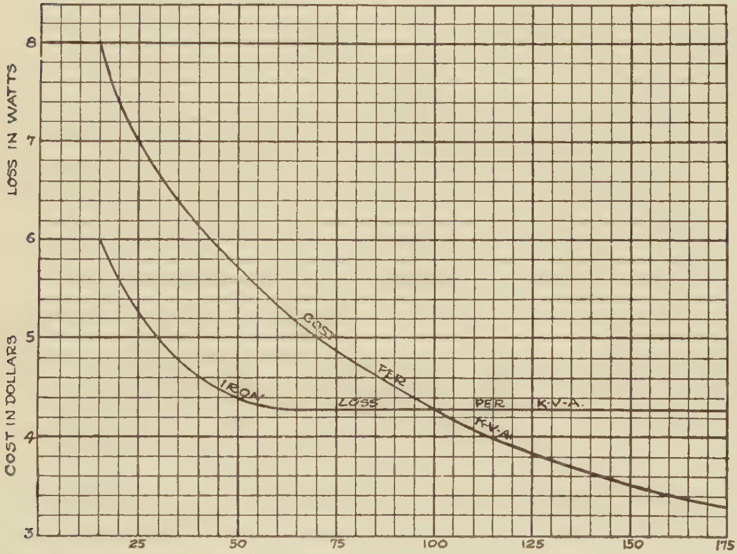


Fig. 181. Transformer Costs and Losses.

iron losses per kv-a. than larger ones, as is shown by the curves in Fig. 181, which apply to 2300 volt transformers.

The transformer cost and losses, therefore, increase as the size of conductor is decreased, and a point may be found by trial at which the sum of all elements of cost is a minimum.

Illustration. — Assume a load density of 50 kv-a. per 1000 feet distributed by overhead lines with a uniform load of

5 kv-a. taken off at each pole, with a pole spacing of 100 feet.

With a 3-wire Edison single-phase system operating at 115–230 volts, this represents a current load of 21.7 amperes on each side of the line taken off at each pole.

At 500 feet spacing between transformers the voltage drop is that due to 43.4 amperes per side in the first 100 foot span, and 21.7 amperes in the second span. No current flows in the middle span. The drop to the end of the second span is within 2 per cent when # 4 wire is used as the conductor, and 2 per cent will be taken as the maximum drop in each case.

The capacity in transformers required with 500 foot spacing is two 25 kv-a. units. For other spacings, fractional numbers and non-standard sizes are involved, but the data for the cost of these may be taken from the curves in Fig. 181, in order to reach a consistent result. In a main several thousand feet in length these fractional numbers and non-standard sizes would become integral numbers and would approach standard sizes.

In the following table showing the results of the calculation, the total annual cost is the sum of (*a*) 11 per cent on the cost of the weatherproof wire at 15 cents per pound, (*b*) 13 per cent fixed charges on the cost of transformers and their supporting poles and accessories, and (*c*) the cost of the iron loss taken as continuous at .7 cent per kilowatt-hour.

The total cost is seen to be a minimum at 600 to 700 feet spacing between transformers, though the differences between the minimum cost and the costs of longer and shorter spacings are not great. The costs are shown graphically in Fig. 182.

It is evident that the common practice of providing a transformer at street intersections with blocks of 500 to 600 feet in length is based on good economics, and that spacings of 1000 feet or more are not economical as a basis of ultimate development. In building lines for future growth, it is usu-

50 KW. PER 1000 FEET OVERHEAD

Transf. Spacing Feet	Size Cond. 1000 C.M.	Conductors		Transformers					Iron Loss		Total Annual Cost
		Cost	11%	No. and Size	Cost: Transf.	Cost: Pole	Cost: Total	13 %	Kw.-hours	Cost .7 cent	
400	26	49	5.4	2.5–20	372	125	497	64.7	2420	16.9	88.0
500	41	74	8.1	2.0–25	350	100	450	58.5	2350	16.4	83.0
600	66	114	12.5	1.66–30	330	83	413	53.5	2190	15.3	81.3
700	83	150	16.5	1.43–35	317	72	389	50.5	2070	14.5	81.5
800	133	220	24.2	1.25–40	306	63	369	48.0	2010	14.1	86.3

200 KW. PER 1000 FEET UNDERGROUND

Transf. Spacing Feet	Size Cond. 1000 C.M.	Cost	11%	No. and Size	Transf.	Vault	Total	13 %	Kw.-hours	Cost .7 cent	Total Annual Cost
400	106	512	56.5	2.5–80	960	2000	2960	325.	7430	52.0	434.
500	166	717	79.0	2.0–100	880	1600	2400	264.	7360	51.5	394.
600	250	975	107.0	1.66–120	770	1400	2170	239.	7290	51.0	397.
700	350	1260	138.5	1.43–140	710	1300	2010	221.	7220	50.5	410.
800	500	1650	181.0	1.25–160	660	1250	1910	210.	7150	50.0	441.

450 KW. PER 1000 FEET — 4 WIRE, 3 PHASE UNDERGROUND

Transf. Spacing Feet	Size Cond. 1000 C.M.	Cost	11%	No. and Size	Transf.	Vault	Total	13 %	Kw.-hours	Cost .7 cent	Total Annual Cost
400	133	606	67.0	7.5–60	2475	4000	6475	711.	17,100	120.	898.
500	212	865	95.0	6.0–75	2200	3200	5400	594.	16,900	118.	807.
600	350	1260	139.0	5.0–90	2025	2800	4825	530.	16,700	117.	786.
700	500	1650	181.0	4.3–105	1900	2500	4400	484.	16,500	115.	781.
800	700	2200	242.0	3.75–120	1800	2250	4050	445.*	16,350	114.	801.

* Fixed charges on underground transformer banks taken at 11 per cent.

ally desirable to provide for some years ahead, since the cost of replacing a secondary main by larger wire is several times as great as the original cost. Large wire and long spacings are, therefore, justifiable in a growing district when provision

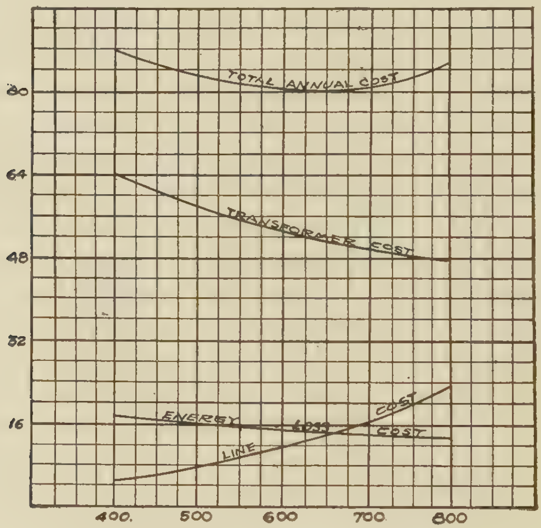


Fig. 182. Cost of Secondary Main.

is made for adding transformers later in such manner as to shorten the spacings.

The situation when the load density is 200 kv-a. per 1000 feet and the lines are underground, is also shown in the table. In this case, the costs under the column headed "Vault" are those for the cost of a manhole or vault and the accessories provided for the transformers. All of the costs in these tables are necessarily likely to vary considerably under different conditions, and should be considered as merely illustrative, though sufficiently accurate for such purposes.

The third section of the table illustrates a 4-wire, 3-phase system, also underground. The fixed charges on transformer

vault cost are taken at a lower rate, making an average of 11 per cent on the total transformer cost.

The minimum cost is found at spacings of 500 to 600 feet in each case, though with a small range of variation for longer spacings up to 800 feet.

Cable costs are taken at the same values per 1000 feet per 1000 c.m., which were used in determining the economical size of cable circuits.

The economical size of wire for a secondary main, having an evenly distributed load, may be determined by calculating a corrected loss factor to allow for the fact that the current tapers off with each 100 feet and using the method outlined for feeder circuits. Such calculations usually give sizes somewhat larger than are necessary to give 2 per cent drop, except when the transformer spacing is over 600 feet and the conductor sizes are larger than # 2. In such cases, the inductive component of voltage drop is sufficient to bring the regulation up to 2 per cent or even more, with the economical size.

Diversity Factor. — In the distribution of electricity for general lighting and power purposes, the maximum demands of consumers are made at different hours of the day, and vary from day to day during the week and from month to month during the year. The maximum demands of lighting consumers are affected by the changing seasons, by the character of the population served, and by the nature of the premises in which the lighting is used.

The residence consumer varies his demands according to the size and character of his dwelling place, having his house well lighted at times and almost totally dark on other evenings. Perhaps his neighbors are well lighted up on the evenings when he is not home. Thus the maximum demands of individual consumers come on different days or at different hours of the day so that their sum is much greater than the

highest demand made upon the distributing system at one time.

With store and other commercial lighting, the demands of the individual users are apt to be more uniform, since the conditions under which lighting must be used are fixed by practical necessity and by customs which the user is not at liberty to ignore. The proprietor of the store must burn his window lights in order to compete with his neighbors, and the owner of the factory must furnish his employees sufficient light to enable them to work to advantage. The diversity factor between such consumers is therefore smaller than it is between residence consumers.

The demand for electricity for power purposes is greatest during the hours when the lighting load is smallest. The combined effect of these influences is to produce a smaller maximum demand at the point of supply than would be required if these demands were coincident. The sum of the maximum demands of individual consumers is greater than that on the distributing mains from which they are supplied. The sum of the maxima on distributing mains is greater than that of the feeder, the sum of the feeder maxima is greater than that at the substations, and the sum of the substation maxima is more than the coincident maximum of the generating station.

The quantitative expression of this relation between the individual demands of the members of a group of users of electricity to the maximum simultaneous demand at the point of supply is called the Diversity Factor of the group, or the Group Diversity Factor.

The definition of the Diversity Factor of a group has been stated in the following form:

"Group Diversity Factor is the ratio of the sum of the maximum power demands of the subdivisions of any system or part of a system, to the maximum demand of the whole

system or part of the system under consideration, measured at the point of supply."

For illustration, if the sum of the individual demands of a group of 50 residence consumers is 30 kw. and the maximum demand made by this group upon the transformer which supplies them is 10 kw., the Diversity Factor of the group is $\frac{30}{10} = 3$.

Or if the sum of the maxima of a group of feeders supplying a district is 2300 kw. and the maximum demand upon the substation which supplies them is 2000 kw., the group diversity factor of these feeders is $\frac{2300}{2000} = 1.15$.

Similarly one may derive group diversity factors for the transformers supplying a district, or for a group of substations or towns making up a large system.

Nature of Diversity. — The existence of a diversity factor is thus due to the differences in the maximum demands of different consumers as to the hour of the day and as to the days of the season, or year. The former may be termed daily diversity and the latter, seasonal or yearly diversity.

Daily diversity is that which arises from the fact that different consumers make their heaviest demands at various hours of the same day. This is illustrated by the load diagrams of Fig. 183 which shows the daily diversity between power users, lighting consumers and electric garages.

Seasonal diversity, or yearly diversity, is that which is due to the fact that different consumers make their maximum demands on different days of the season, or year, respectively.

Weekly and monthly diversity factors may also be required for special purposes, at times.

Familiar examples of seasonal diversity are found in the manufacture of ice, amusement parks, irrigation pumping,

etc. Weekly diversity is exemplified in the heavy lighting loads that occur on Saturdays in certain places, while the maximum use of power and lighting in industrial establishments occurs on other days of the week and is below normal on Saturdays. A considerable part of the diversity of residence consumers is seasonal or monthly rather than daily. There are always certain ones of a group of residence users

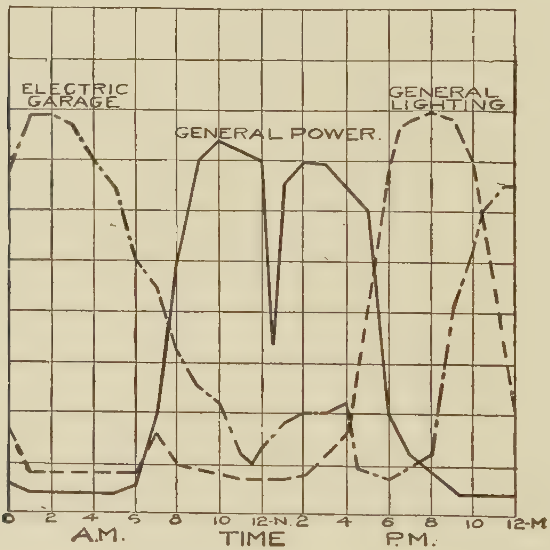


Fig. 183.

who are away from home for an evening and whose requirements are therefore below normal. On the other hand, every member of the group is likely to have his home open to guests on certain evenings of the year when he uses more than his average requirements. Thus the sum of the maxima of the members of the group is much higher than the coincident demand at the transformer and we have seasonal diversity among residence consumers.

The determination of diversity factors must therefore be

based upon records of maxima for the months of the year as well as upon load diagrams for the day on which the maximum coincident demand of the year occurred.

The diversity factor, as defined by the standard definition, may apply to a group of consumers in a given locality served by a single transformer, to the feeders supplied by a single substation or to a group of towns supplied by a transmission system. It may also be applied to a group of classes such as general power, commercial lighting, residence lighting, and others whose hours of use are known. It implies the existence of a group, and is therefore a group diversity factor. Its effect is to produce a coincident demand upon the source of supply which is less than the sum of the separate demands. It reveals nothing, however, as to how much any individual user or group of users contributes to the reduction in demand.

For certain purposes it is necessary to know how much each individual of a group contributes to the group diversity. Electric garages, ice manufacturers, water pumping plants and others which have very high diversity when taken in comparison with the general system load diagram, require special consideration and a further definition of diversity factor. This may be termed the individual diversity factor and is defined as follows:

"Individual diversity factor is the ratio of the maximum power demand made by any subdivision of a system, to the coincident demand made by such subdivision at the hour of the maximum load upon the source of supply."

If, for instance, a class of consumers, such as ice manufacturers, makes a demand of 2000 kilowatts during the summer months, and a demand of 200 kilowatts at the hour of the annual maximum in the winter months, the individual diversity factor of ice manufacturers as a class is $\frac{2000}{200} = 10$.

A clear conception of the relation of the group diversity factor of a group to the individual diversity factor of a member of the group is quite essential in determining the investment portion of the cost of serving any class or community of consumers.

Illustration. — For example, take a purely residence suburb which is a part of a district supply system from which commercial lighting, industrial power and other classes of service are supplied in other localities. In this residence suburb, the group diversity factor will be about 3.5, that is, the sum of individual consumers' demands will be about 350 kilowatts for each 100 kilowatts of demand at the substation supplying this suburb.

However, the individual diversity factors of the various consumers in this suburb may range from 1 to 10 or more. The resident who happens to have his house open for a social event and is using his annual maximum demand at the hour of the annual substation maximum has an individual diversity factor of 1. The resident whose house is empty at that hour, with perhaps one 50-watt lamp burning, has an individual diversity factor of 10 or more. The weighted average of the individual diversity factors of all the consumers is the group diversity factor.

The load of the residence suburb, considered now as a wholesale user from the transmission system, is combined with the loads of other towns, which affects the total demand upon the transmission system and power station. There may be a coincident demand of 20,000 kilowatts on the power station, with demands at various times on the substations aggregating 30,000 kilowatts. The group diversity factor of all the substations is 1.5. The individual diversity factor of the residence suburb may be anything from 1 to 5 or more. If the annual system maximum occurs on Christmas Eve, the resi-

dence suburb will probably have an individual diversity factor of very nearly 1, but if the annual system maximum occurs during daylight hours, the individual diversity factor of the residence suburb may be 10 or more. These conditions are illustrated by the load diagrams in Fig. 184, in which curve *C* is the load diagram for the residence suburb for December 20th, the day of the general system maximum, *D* is the curve for the day on which the annual maximum of the substation

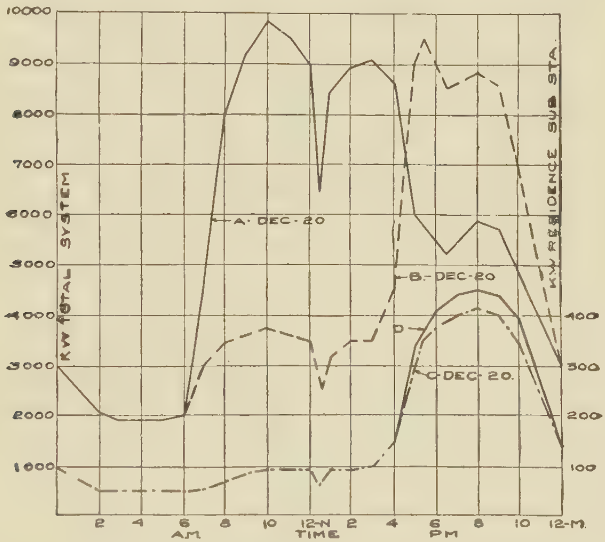


Fig. 184.

occurred, and *A* and *B* are typical system load diagrams for systems in which the day power and evening lighting loads respectively predominate. If the residence substation is a part of a system with the load diagram *A*, the individual diversity factor of this substation maximum of 450 kilowatts to the substation load of 90 kilowatts at 10 A.M., the hour of the system maximum, is $\frac{450}{90} = 5$.

If this substation is a part of a system such as that represented by load diagram B, the individual diversity factor of the substation at 5.30 P.M., on December 20th, the day of the general system maximum, is $\frac{450}{350} = 1.28$.

Group Diversity Factors of Consumers. — An analysis of diversity factors for various classes of consumers in the city of Chicago has been made by the authors, based upon observations made at various points in the alternating-current distributing system.

The observations were taken at the consumers' meters, at the line transformers, at the substation switchboard and at the generating station. The relation of these various points is illustrated diagrammatically in Fig. 185.

Consumers of electricity were classified as residence light, commercial light, general power and large users. The commercial light includes the average small and medium-sized stores and shops whose maximum demand is under 50 kw.; general power includes all miscellaneous power users having less than 50 kw.; while large users are the light and power consumers having 100 to 500 kw.

The observations made and results calculated for the various classes of consumers are presented in the accompanying table. Group A is a residence block supplied by one transformer, in which there are 34 consumers having a connected load of 18 kw. or an average of .53 kw. per consumer. The sum of the consumers' maxima is 12 kw., while the actual maximum as measured on the transformer is 3.6 kw. The ratio of the consumers' maxima to the transformer maximum is 3.33, which is the diversity factor between the consumers in this block. The average load factor of this group of consumers is 7 per cent, considered individually, while the load factor of the energy delivered from the transformer is 23.1 per cent.

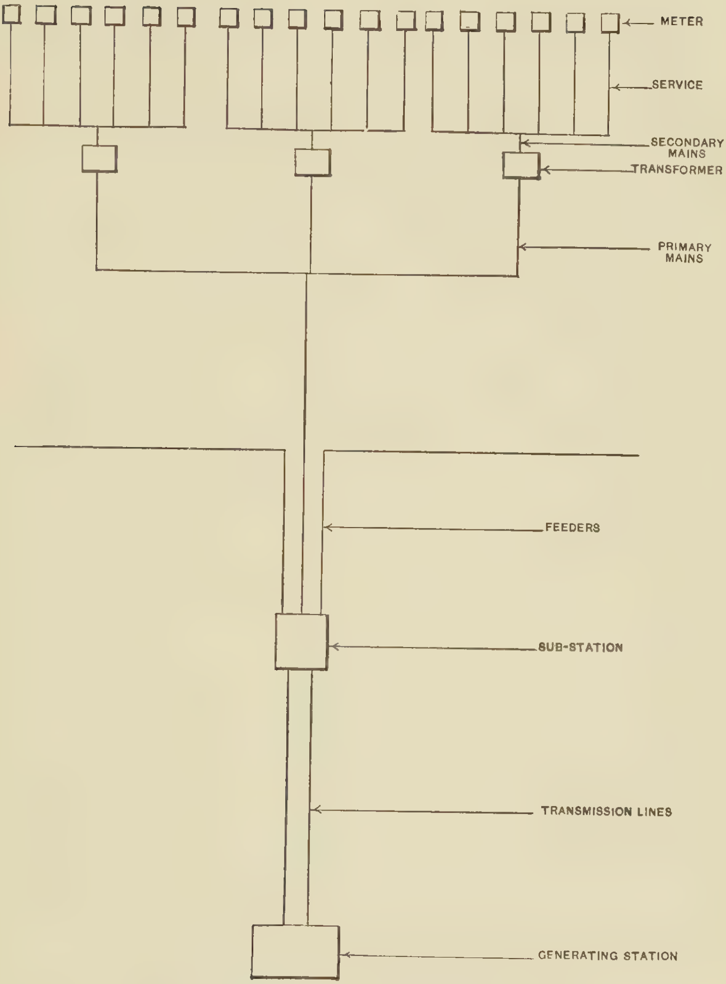


Fig. 185. Elements of a Distribution System.

RESIDENCE LIGHTING

Group	No. of cons.	K.W. conn. per cons.	Sum of cons. max.	Max. of group	Diversity factor	Aver. cons. load factor.	Group load factor
A	34	.53	12	3.6	3.33	7	23.1
B	185	.53	68	20.	3.40	7	23.8
C	167	.87	93	28.	3.32	7.3	24.0
Aver.	128	.68	57	17.2	3.35	7.1	23.9
COMMERCIAL LIGHTING							
D	46	1.28	46	33	1.40	13	18
E	79	.74	36	26	1.40	11	16
F	160	.53	62	41	1.51	10	15
Aver.	95	.70	48	33	1.46	10.8	15.7
G	221	2.70	403	270	1.48	13	19
GENERAL POWER							
		H.P.	K.V.A.	K.V.A.			
H	29	1.3	30	21	1.43	15	21
I	18	3.3	40	25	1.60	16	26
J	11	11.8	90	65	1.39	18	28
K	25	6.0	100	70	1.43	21	30
Aver.	21	4.5	65	45	1.44	17.5	26

Group B is a similar block having 185 consumers with the same average connected load. The sum of the consumers' maxima is 68 kw., the transformer maximum is 20 kw., the diversity factor is 3.4 and the transformer load factor is 23.8.

The premises lighted by these two transformers were practically all apartments and the public halls of the same.

In Group C the premises were about two-thirds small apartments and the remainder large apartments and residences. This accounts for the greater connected load and the larger average load on this transformer. The diversity factor, however, remains practically the same as in the previous cases.

The determination of the sum of consumers' maxima in cases where the connected load is less than 1 kw. is based upon averages worked out from the readings of demand meters.

The schedule of individual consumers' demands used in these calculations was as follows:

Connected load 50-watt equivalent.	3	5	7	9	11	13	15	17	19
Maximum 50-watt equivalent.....	3	5	6	6.5	7	8	8	9	10

These maxima were determined from the averages of the demand meter readings of over 20,000 residence consumers.

The transformer maxima were taken by the use of Wright demand meters during the winter months, this being the time when the maximum load occurs in the districts in which observations were taken.

Of the three groups of commercial light consumers, it will be noted that Group D consists of 46 consumers having an average connected load of 1.28 kw. The total of the consumers' maxima is 46 kw., the transformer maximum is 33 kw. and the diversity factor is 1.4. This group consists of small stores on an outlying business street, with several restaurants.

In Group E there are 79 consumers having an average connected load of .74 kw. and a diversity factor of 1.4. There are no large stores in this group and no restaurants.

In Group F there are 160 consumers with an average connected load of .53 kw. and a diversity factor of 1.5. This group includes eight or ten apartments above stores and an equal number of offices, lodge halls, etc., which tend to increase the diversity factor and to lower the average consumer's load factor.

Group G is an 18-story office building in which there are 221 consumers including the lighting and general power service of the building owner. The connected load of 603 kw. includes 180 horse power in ventilating fans, pumps and such other machinery as is used in an office building having hydraulic elevators. The average load per consumer is 2.7 kw., the sum of the consumers' maxima is 403 kw., the maximum as measured on the feeder at the substation switchboard is

270 kw. and the diversity factor is 1.48. The consumers' maxima were determined from demand meter readings for the most part in this case. This is not strictly commercial lighting, as the power load could not be measured separately and is included in the maximum of 256 kw. for the building.

Among the general power users, Group H consists of 29 single-phase consumers having a connected load of 37 horse power and an average load of 1.3 horse power. The sum of the consumers' maxima is 30 kv-a., the transformer maximum is 21 kv-a. and the diversity factor is 1.43. These consumers are small shops manufacturing men's clothing.

Group I consists of 18 consumers having 60 horse power in single-phase and three-phase motors whose average horse power connected is 3.3. The diversity factor for this group is 1.6. Ten of these are consumers using less than 5 horse power manufacturing clothing and the other eight are larger consumers using power for various other manufacturing processes.

Group J consists of eleven consumers having an average load of 11.8 horse power whose diversity factor is 1.39. The largest consumer in this group has wood-working machinery which is operated steadily and accounts for the higher transformer maximum and lower diversity factor.

In Group K, 25 consumers have an average installation of 6 horse power with a diversity factor of 1.43. About fifteen of this group are small clothing manufacturers having less than 5 horse power.

The consumers' maxima for these groups were determined on the basis of maximum demands of several thousand similar direct-current consumers who were equipped with demand meters. The transformer maxima were measured between 10 and 11 A.M., this being the hour when the alternating current power load is a maximum in Chicago.

The consumers' load factors which appear in this table for power users were taken from a paper read by Mr. E. W. Lloyd before the National Electric Light Association at its 1909 convention. His results were derived from a large number of demand and wattmeter readings on various classes of power users.

With large users the larger part of the diversity arises between different parts of the premises. In a large mercantile

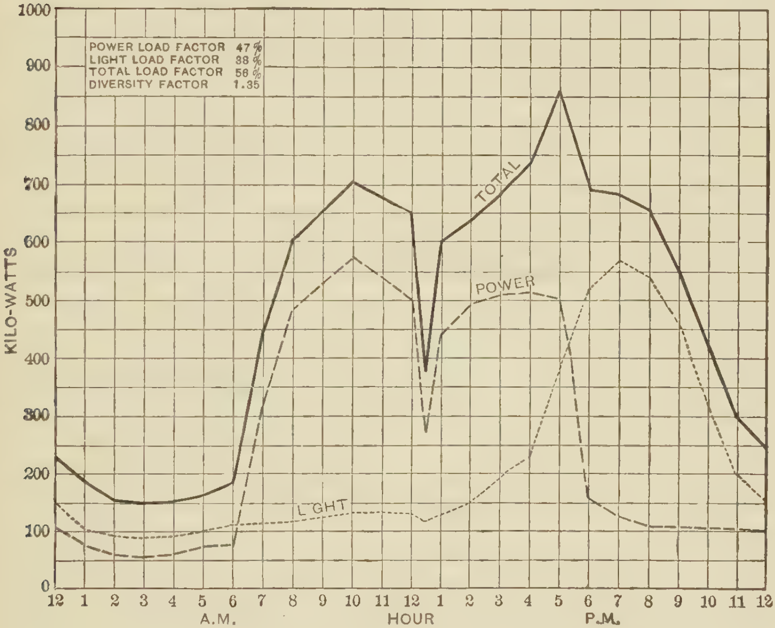


Fig. 186. Diversity between Light and Power Loads.

store there are always some departments where business is dull at a time when it is good in another department and *vice versa*. Likewise in a large manufacturing establishment the requirements of different departments for power vary with different hours of the day and different days of the week. The maximum demands of large users therefore vary by a

smaller percentage from day to day than those of small consumers, and the principal source of diversity between large users arises from differences in the general character of their requirements.

The curves in Fig. 186 show the result of combining the demands of a large day power users and a large evening light users. The sum of the demands of these consumers is 1150 kw., while the coincident maximum demand, which occurs at 5 P.M., is but 850 kw. The diversity factor between these groups of consumers is therefore 1.35.

Diversity between Transformers. — The diversity between different transformers on the same feeder is similar to that between large users. A study of the amount and character of load on the various transformers in conjunction with representative tests of transformer loads makes it possible to derive diversity factors for groups of transformers which are reasonably accurate.

Analyses made of transformers supplying residence territory with about 25 per cent of small store lighting and less than 5 per cent of power load indicate an average diversity factor between transformers of 1.2. Transformers supplying about equal amounts of residence and commercial lighting with 25 per cent of power show diversity factors of about 1.3. Those supplying a large number of scattered power consumers with 40 per cent to 50 per cent of lighting may have diversity factors of 1.8 to 2 between transformers.

These figures of course apply only where the secondary mains are not interconnected.

Diversity between Feeders. — At the substation bus bar there is a further diversity between feeders. In a certain substation having a load of 3500 kw. which is 90 per cent lighting, the maximum loads on most of the feeders occur at 7.30 P.M. in December, the other feeders having their

maxima at 5 P.M. The diversity factor of the feeders in this station during the week of the maximum load of the year was 1.05.

In a 2700-kw. substation the maximum load on 90 per cent of the feeders occurs at 5 P.M., due to a large proportion of store and factory light and power, and the diversity factor between feeders was 1.06 during the week of the maximum load of the year.

In two other substations of nearly the same size about 60 per cent of the feeders have 7.30 P.M. maxima and 40 per cent have 5 P.M. maxima. In these substations the diversity factor was 1.14 and 1.15 respectively during the week of the annual maximum.

In another case where about half of the feeder maxima occur at 5 and half at 7.30 P.M. the feeder diversity factor was 1.36.

Substation Diversity. — In systems having five or more substations there is an appreciable diversity factor of the group in the average system. This arises from the fact that certain substations have larger proportions of power and industrial load than others, and the day and hour of their maximum demand differs from those which serve lighting load in predominance.

This is illustrated by the following table, showing the substation maxima of 10 Chicago substations, together with the demand upon the generating station coincident with the total system maximum load and the individual diversity factors of each substation.

The diversity factor of the group is the sum of the absolute maxima, 57,720 kw., divided by the sum of the coincident demand, 50,120, or 1.15. It will be noted that some of these substations have very small individual diversity factors while those of others are relatively large.

Substation	Absolute maximum kw.	Coincident demand	Indiv. div. fact.
1	3,800	3,600	1.06
2	4,200	3,510	1.26
3	1,770	1,200	1.47
4	5,220	4,050	1.29
5	10,650	8,250	1.29
6	5,220	4,650	1.12
7	4,710	3,840	1.23
8	2,000	11,700	1.03
9	5,100	4,500	1.13
10	5,050	4,820	1.04
Total	57,720	50,120	1.15

In systems supplying an appreciably large proportion of electric railway service there is a considerable diversity factor arising from the fact that railway service demands are transferred from substations near the center of the city to those in the outskirts as the cars progress outwardly during the evening rush hour. The reverse progress takes place in the morning peak but is not concentrated so closely as the evening peak and usually does not fix the maximum demand of the railway portion of the load.

Total Diversity. — The total diversity factor of the generating and distributing system is the continued product of the diversity factors between consumers, transformers, feeders and substations. In the case of residence consumers, the total diversity factor is the product of $3.35 \times 1.3 \times 1.15 \times 1.1$. This amounts to 5.52. For commercial lighting consumers the total diversity factor is 2.41. For general power consumers the total diversity factor is 2.26 and for large users 1.45. These are the diversity factors from the consumer's meter to the generating station.

The average diversity factors for the four classes of con-

sumers and the total diversity factor from the consumer to the generator are presented in the following table.

The total diversity factor of a distributing system is obtained by combining those of the various classes of consumers.

DIVERSITY FACTORS

	Residence light	Commercial light	General power	Large users
Between consumers	3.35	1.46	1.44	....
" transformers	1.3	1.3	1.35	1.15
" feeders	1.15	1.15	1.15	1.15
" substations	1.1	1.1	1.1	1.1
Consumer to transformer	3.35	1.46	1.44	....
" " feeder	4.36	1.90	1.95	1.15
" " substation	5.02	2.19	2.24	1.32
" " generator	5.52	2.41	2.46	1.45

Relation to Load Factor. – The relation of the group diversity factor to group load factor is direct and comparatively simple. When, for instance, a group of retail users is considered, the load factor at the transformer supplying the group is the product of the average individual load factor by the group diversity factor. With 100 residence users having a yearly group diversity factor of 3, and an average annual load factor of 7 per cent, the annual load factor at the transformer is $3 \times 7 = 21$ per cent.

To state it in another way, if the average annual consumption of the members of the group is 250 kilowatt-hours, and the average annual load factor of each is 7 per cent, the average maximum demand of the individual user is $\dfrac{250}{.07 \times 8760} =$ 0.408 kilowatts. The sum of the 100 individual demands is therefore $100 \times 0.408 = 40.8$ kilowatts. Since the yearly group diversity factor is 3, the coincident demand at the transformer is $\dfrac{40.8}{3} = 13.6$ kilowatts. This transformer delivers

$100 \times 250 = 25{,}000$ kw. hrs. per year to the group and its annual load factor as a wholesale consumer on the distributing system is $\frac{25{,}000}{13.6 \times 8760} = 21$ per cent.

This rule may be applied to any class or group of users whose average individual annual load factor, annual consumption, and yearly group diversity are known. It is equally applicable to a group of substations in a large system.

The energy converted in the group of substations amounts to 153,200,000 kw. hours annually, and the annual load factors vary from 19 per cent to 35 per cent, the average being 30.5 per cent.

The group diversity factor being 1.15, the annual load factor at the point of supply is $30.5 \times 1.15 = 35.0$ per cent.

This may be shown also from the annual output and coincident demand, the output being 153,200,000 and the demand being 50,120 kw.

$$\text{Load factor} = \frac{153{,}200{,}000}{50{,}120 \times 8760} = .35.$$

There is no direct relation between the individual diversity factor and the individual load factor, except that consumers having a high load factor are more likely to come on the peak and hence to have a small diversity factor and *vice versa.* The off peak consumer may, of course, be an exception to this rule as he may have a relatively high load factor, but also a high individual diversity factor because of the special contract arrangement not to use energy at the usual hours when the system maximum load comes on.

In the table of substation maxima, the first one in the list has an annual load factor of 35 per cent but its maximum comes so nearly coincident with that of the whole system that its diversity is small, the individual diversity factor being only 1.06. The second one in the list has an annual load factor of

37 per cent and yet its individual diversity factor is 1.26, because its maximum load occurs at a different hour from that of the general system. Thus one of these substations has a diversity factor higher than that of the group, while that of the other is lower, though their load factors are about the same.

Relation to Investment. — The effect of diversity factors upon the various parts of the generating and distributing plant is to reduce investment and hence the demand portion of charges for service. This effect is so material as to justify the most careful analysis of load conditions in their relation to diversity of demand. Such analyses are of value in solving the problems incident to fixing equitable rates for various classes of service, in making subsequent adjustment of established rates, and in revealing the relative rates of returns produced by various classes of users under existing rate schedules. It is of the utmost importance that the methods pursued in determining the cost of electric service be based upon correct principles and that the data at hand be intelligently applied.

As a basis of illustration, it will be assumed that an alternating-current central-station system has been developed to a point where it has 25,000 kilowatts in generating plant capacity and a maximum load of 20,000 kilowatts at a cost of $8,100,000 or $405 per kw. load.

The apportionment of the capital invested is further assumed to have been made as shown in the table below. This apportionment is roughly representative of an average system in a medium-sized city without any considerable suburban distribution. In a district supply system covering a large area of scattered towns and cities, the transmission system would be a larger percentage of the total and other parts might be materially different. The numerical values derived

from these figures as a basis are therefore to be considered only as applying to a system of the type assumed, and, being hypothetical, should be considered merely as illustrating the method of calculation.

ASSUMED ALTERNATING CURRENT CENTRAL STATION SYSTEM

	Group Div.		Kw. useful load	Full load eff.	Actual kw. demand	Invest-ment per kw.
	Investment	Factor				
Generating station...	$2,350,000	...	16,050	....	20,000	$117.50
Transmission system.	450,000	...	.....	0.95	......	21.50
Substation...........	800,000	1.1	17,650	0.912	21,000	38.00
Distribution lines....	2,750,000	1.15	20,300	0.802	23,200	119.00
Transformers........	350,000	1.3	26,400	....	26,400	13.00
Meters..............	500,000	...	.....	....	......	......
Miscellaneous.......	900,000	...	.....	....	......	......
Total............	8,100,000	...	.....	0.802	......	......

The actual kilowatt demand which appears in the next to the last column is the net result of the application of both diversity factor and full-load efficiency. The 20,000-kw. load on the generating station is made up of 16,050 kilowatts of useful load and 3950 kilowatts of losses in the transmission, conversion and distribution systems. If the efficiencies are assumed at 95 per cent for the transmission system, 96 per cent for transformer substations and 88 per cent for the distribution system, the net overall efficiency would be 80.2 per cent.

If there were no losses, the " actual kw. demand " would be the same as the " useful load."

When the losses are taken into account:

The sum of the feeder maxima at 88 per cent efficiency is

$$\frac{26{,}400}{1.3 \times 0.88} = 23{,}200 \text{ kilowatts.}$$

The sum of the substation maxima at 96 per cent efficiency is

$$\frac{23{,}200}{1.15 \times 0.96} = 21{,}000 \text{ kilowatts.}$$

The maximum at the generating station at 95 per cent efficiency is

$$\frac{21{,}000}{1.1 \times 0.95} = 20{,}000 \text{ kilowatts.}$$

These are the loads which would be observed in this system at each point where the group of elements is supplied.

The investment per kilowatt in the last column is determined by using the kilowatt actual demand at the point of supply, as shown in the previous column.

From this data the investment required to serve a given class of consumers may be determined, if the group diversity factor of the class is known, and with the investment determined, it is but a step to determine what the demand portion of the charge to that class of consumers should be.

In the distributing system investment, there are, however, such wide variations of the cost per kw. under different conditions that some attention should be given to the costs for classes of users which are materially higher or lower than the average.

The investment per kw. is very greatly affected by the density of the load, that is, by the load served per square mile. For instance, in outlying districts where there are less than 10 consumers per block, the investment may often be as much as \$300 per kw. for distribution, and in manufacturing districts or retail business districts, it may be as low as \$60 or less. This is due in large measure to the fact that pole lines or conduit lines, primary mains and secondary mains must all be installed before any consumer can be served. The minimum capacity which it is possible to install for mechanical reasons is so great that the initial equipment remains the permanent

equipment in many portions of the city, and additional consumers increase the load density without adding proportionately to the investment. The kw. per square mile can be increased tenfold above its initial value in many cases without necessitating additional investment except for feeders, transformers and service connections. These reinforcements cost only \$25 to \$40 per kw. and thus tend to lower the average cost per kw. as load is added. In a similar way, large users may be taken on at only the cost of feeder and transformer capacity and the distribution investment for consumers whose load is 200 kw. and upward is frequently as low as \$50 per kw. Thus, for retail users, the investment per kw. in the distribution system here assumed would be from \$50 to \$200 in order to make the average of the whole system \$119 per kw.

Investment for Residence Consumers. — When it is desired to determine the investment required for residence consumers, for instance, and it is known that the group diversity factor of this class is 3, the result may be reached approximately as follows: Assume that 100 such consumers are to be served and that their average individual maximum demand will be .6 kw. The sum of the individual demands is then $100 \times .6 = 60$ kw. and, the group diversity factor being 3, the demand on the transformer is $\frac{60}{3} = 20$ kw.

The group diversity factor of the transformers being 1.3, the demand on the feeder will be $\frac{20}{1.3} = 15.4$ kw., plus losses at 98 per cent efficiency, or $\frac{15.4}{.98} = 15.7$ kw.

The diversity factor of the feeders being 1.15 and the efficiency of the distributing circuits being 90 per cent, the demands on the substation will be $\frac{15.7}{1.15 \times .90} = 15.2$ kw.

The demand on the power station at the time of the maximum load on the system, with a substation diversity factor of 1.1 and an efficiency of 90 per cent for transmission and conversion equipment, would be $\frac{15.2}{1.1 \times .90} = 15.3$ kw.

The investment required to carry this group of consumers therefore is summarized as follows, using the units of cost assumed, in the above table, and taking meters at $7.00 each.

100 meters @ $7.00	$700.00
20 kw. transformer capacity @ $13.00 per kw.	260.00
15.7 kw. distribution line capacity @ $200 per kw.	3140.00
15.2 kw. substation capacity @ $38.00 per kw.	577.00
15.2 kw. transmission line capacity @ $21.50	327.00
15.3 kw. generating station capacity @ $117.50	1798.00
Miscellaneous investment, 12.5 per cent	850.00
	$7652.00

Total investment per kw. gen. sta. load	$500.00
Total investment per kw. consumers demand	127.50

If the fixed charges on the investment in the plant are taken at 13 per cent, the demand portion of the cost of serving the residence consumer in this group is $.13 \times \$127.50 = \$16.57$ per annum, or $1.36 per month per kw. of demand at the consumer's premises. For the average residence consumer here assumed to have a maximum demand of .6 kw., the demand cost is $.6 \times \$1.36 = \$0.81$ per month.

This, of course, does not include any operating cost or consumer cost, but is purely that portion of the cost due to the fact that the consumer's demand requires a certain portion of the plant to be reserved for his use.

Investment for Commercial Consumers. — In the case of commercial lighting and power consumers of the retail class, the diversity factor is lower and the plant required is some-

what more for a consumer having the same individual demand.

Assuming a group of 100 commercial light and power consumers, having loads of less than 10 kw. and whose individual demands average 3 kw., the investment cost per kw. for the distribution system is somewhat less and may be taken at \$150 per kw. for purposes of illustration.

The demand at the transformer, with a group diversity factor of 1.4, is $\frac{3 \times 100}{1.4} = 214$ kw. The load on the feeder at 98 per cent transformer efficiency and 1.3 diversity factor of transformers is $\frac{214}{.98 \times 1.3} = 165$ kw. At the substation the load is $\frac{165}{.90 \times 1.15} = 159$ kw. and at the generating station it is $\frac{159}{.9 \times 1.1} = 161$ kw.

The investment may be summarized as follows:

100 meters @ \$9.00 each	\$900.00
214 kw. transformer capacity @ \$13.00........	2,782.00
165 kw. of distributing line capacity @ \$150....	24,750.00
159 kw. of substation capacity @ \$38.00.......	6,042.00
161 kw. of transmission capacity @ \$21.50.....	3,461.00
161 kw. of generating capacity @ \$117.50......	18,917.00
Miscellaneous investment @ 12.5 per cent......	7,100.00
	\$63,952.00

$$\text{Investment per kw. generating station load} = \frac{63{,}952}{161} = 400.00$$

$$\text{Investment per kw. consumer's demand} = \frac{63{,}952}{300} = 213.00$$

It is to be noted that the meter investment is a much smaller part of the total investment required for this class of consumers than it is for the small residence consumer. The

meter investment for this class is but \$3.00 per kw. of consumer's demand while for the small residence consumer it is \$11.66 per kw. The fixed charges are $.13 \times 213 = \$27.70$ per annum or \$2.31 per kw. per month, or \$6.93 for a 3 kw. consumer.

In the case of the wholesale user with a demand of about 200 kw. or more, the feeder and a small proportion of the primary main system are the only parts of the distribution system needed to meet his requirements aside from transformers. The total value of these will be taken at \$50 per kw. in this case. The total investment would be as follows for a consumer having a 200 kw. demand and an individual diversity factor as related to the substation of 1.25:

Metering equipment	\$30.00
Transformers, 225 kw. @ \$7.00 per kw.	1,575.00
Distribution line, 160 kw. @ \$50 per kw.	8,000.00
Substation capacity, $\frac{160}{.90 \times 1.15} = 154$ kw. @ \$38	5,852.00
Transmission capacity, $\frac{154}{.9 \times 1.1} = 155$ kw. @ \$21.50	3,242.00
Generating capacity, 155 kw. @ \$117.50	18,212.00
Miscellaneous investment, 12.5 per cent	4,620.00
Total	\$41,531.00

$$\text{Investment per kw. generating station load} = \frac{41,531}{155} = \$270.$$

$$\text{Investment per kw. consumer's demand} = \frac{41,531}{200} = \$207.$$

Thus the fixed charges for the wholesale consumer are $.13 \times 207 = \$26.91$ per kw. of consumer's demand per annum.

In case the wholesale consumer requires a class of service which has a higher diversity factor than 1.25, this element of the cost may be still further reduced. For instance, in the case of long hour users such as ice manufacturers who can arrange their hours of operation so as to shut down most of their plant during the hours of the day in the months of the year when the general system maximum occurs, it is possible to eliminate the greater part of the charge for generating station capacity and in some cases the transmission line and substation investment. This may amount to approximately one-half the total investment.

CHAPTER XV

PROPERTIES OF CONDUCTORS

The fundamental unit in electrical distribution is the conductor. A thorough knowledge of the physical properties of the conductors of electricity is therefore indispensable to the distribution engineer.

While all metals are conductors of electricity, each has its own characteristics of resistance, temperature-coefficient and mechanical strength.

Copper, being among the best conductors and sufficiently plentiful in nature, is the metal most commonly employed for distribution work. Aluminum is used in transmission work to some extent, because of its low specific gravity. Iron is used as an electrical conductor for rural lines and in railway work, where the rails carry the return current to the power house, and in third rail systems the supply to the motor cars is so carried.

German silver and other alloys are used in making resistance coils for rheostats carrying small currents. Silver is a better conductor than copper, but its value is too great to permit its use for electrical work, except for special purposes where no considerable quantity is required.

Area of Cross-section. — The area of cross-section of wires is commonly measured in circular mils, a circular mil being the area of a wire having a diameter of .001 inch. A circular mil therefore has an area of $.785 \times (.001)^2 = M$. A wire having a diameter of 325 mils or .325 inch has an area of $.785 \times (.325)^2 = M \times (325)^2$. The area of a wire having a diam-

eter of .325 inch is therefore 105,500 circular mils, which is the area of # 0 wire A.W. gage.

The cross-section of a wire in circular mils is therefore the square of its diameter expressed in mils. The area of a conductor 1 inch or 1000 mils in diameter is 1,000,000 circular mils.

Likewise, in reckoning the area of rectangular conductors, the area in square mils is the product of the width by the thickness expressed in mils. A square mil is $\frac{1}{.7854} = 1.274$ times a circular mil, and a circular mil is .7854 of a square mil. It is customary to express areas in square millimeters where the metric system is employed.

Wire Gages. — The wire gage consists of a series of numbers used in practice as a means of identification of the various sizes of wires. The gage numbers are made intelligible by a table giving diameters of each size, weight per 1000 feet, feet per pound and, in the case of wires used as electrical conductors, resistance data per 1000 feet, etc.

In earlier years different manufacturers adopted their own wire tables to accompany similar series of gage numbers. Thus the makers of steel wire had one gage and the makers of copper wire a different one. European gages were still different from those of American manufacturers.

Steel Wire Gage. — The Washburn and Moen gage was established in 1830 for use in the manufacture of iron and steel wire, and was later used by John A. Roebling & Sons for similar purposes. The American Steel and Wire Company, upon absorbing the Washburn & Moen Company, adopted its steel wire gage and gave it the name of the new company.

In 1912 the U. S. Bureau of Standards made a complete study of wire gages, the results of which were published in its

Bulletin 31. This report showed that the great majority of steel wire was being made in accordance with the American Steel and Wire Gage and that this gage was quite well adapted to the purpose. It recommended this gage, therefore, as the "Steel Wire Gage" for the United States, and the American Institute of Electrical Engineers adopted this name as standard.

The other gages which are used to a limited extent are the Birmingham (sometimes called the Stubs Wire Gage), the Old English and the Stubs Steel Wire.

The Birmingham gage is said to have been established in the 18th century and was based upon the drawing process. # 0 was the rod from which wire drawing was started; # 1 was the first reduction; # 2 the second and so on. Its gradations are rather irregular, for this reason, in some parts of the scale.

The British government made certain changes in the Birmingham gage with a view to smoothing out these irregularities and adopted the revised gage as its "Standard Wire Gage" by which it is now known.

American Wire Gage. — The American Wire Gage is used exclusively in America for copper wires and other wires intended for use as electrical conductors. It was devised by J. R. Brown of the Brown and Sharpe Mfg. Co. in 1857, and was for many years referred to as the B. & S. gage. The American Institute of Electrical Engineers adopted this gage as standard under the name American Wire Gage and this is the term now used by the Brown and Sharpe Co. as well as other manufacturers of electrical conductor wires in designating their output.

This gage was scientifically conceived as it is based upon a simple mathematical formula, which gives regular gradations in size from largest to smallest, and meets all practical requirements well.

The sizes grow smaller in diameter as the numbers grow larger, thus following the wire drawing process in a general way.

The diameter of 4/0, which is the largest size, is .46 inch, and the diameter of # 36 is .005 inch. The diameter of any wire in the series is 1.1229 times that of the next higher number of the wire gage. Every size is 2.005 times the diameter of the sixth size smaller.

Thus # 0 has a diameter 1.1229 times that of # 1 and 2.005 times that of # 6. In area the ratio of any size to the next smaller size is 1.261, and any size has twice the area of the third smaller size. The area of # 0 is 1.261 times that of # 1, and 2.005 times that of # 3. The area of the second larger size is 1.59 times that of any particular size which may be known.

Thus if it is carried in mind that # 10 has an area of 10,380 circular mils, and a diameter of .1019 inch, it is a comparatively simple calculation to determine the diameter or area of any larger size. It is also useful to remember that # 0 has approximately 10 times the area of # 10 and therefore $\frac{1}{10}$ the resistance.

It is also useful to remember that # 5 weighs 100 lb. per 1000 feet, as the weight per 1000 feet of any other size may be readily found by the use of the ratios above given for the area of cross-section.

For instance, knowing that # 10 has an area of 10,380 circular mils, what is the area of # 3 wire? As the area doubles every third size larger, # 7 is double # 10, or 20,760 circular mils, and # 4 is double # 7, or 41,520 circular mils. # 3 is 1.26 × 41,520 or 52,300 circular mils.

Or, if the area of a smaller wire is desired, the next size smaller than 10 is .80 of the area of # 10, the second size is .63 and the third size is .5 of # 10. Thus the area of # 13 is .5 of 10,380, or 5190 circular mils, and the area of # 14 is .8 × 5190 = 4150 circular mils.

In a similar way, the resistance per 1000 feet of any size may be determined approximately without reference to a table, if the resistance of one size is known. As resistances decrease with increasing area, the resistance of any wire is 1.26 that of the next larger size, or .80 that of the next smaller size. It is 1.59 times that of the second larger size or .63 that of the second smaller wire and so on.

The values of area, weight and resistance may be calculated from the following formulæ, if no values are available:

If N represents the gage number (# 0 = 0, # 00 = − 1, # 000 = − 2 and # 0000 = − 3) the resistance per 1000 feet is

$$R = 10^{\frac{N-10}{10}}. \quad \text{Log } (10\, R) = \frac{N}{10}.$$

The weight per 1000 ft. bare is

$$W = 10^{\frac{25-N}{10}}. \quad \text{Log } W = \frac{25 - N}{10}.$$

The area in circular mils is

$$M = 10^{\frac{50.2-N}{10}}. \quad \text{Log } M = \frac{50.2 - N}{10}.$$

These formulæ may be readily utilized without access to a table of logarithms by resorting to the ordinary 10-inch slide rule.

For instance, if it is desired to know the resistance per 1000 feet of # 2, or # 4 wire, the wire numbers are inserted in the formula log $(10\, R) = \frac{N}{10}$ and the procedure is as follows: log $(10\, R) = \frac{2}{10}$.

Setting the figure 2 on the evenly divided scale of the slide the value of $10\, R$ is read as 1.585 on the lower scale of the rule at the opposite end of the slide. $R = \frac{1.585}{10} = .1585$ the re-

sistance per 1000 feet of # 2 wire. In a similar way, setting the slide at 4, the resistance of # 4 is seen to be .251 ohm per 1000 feet.

If the weight is desired for these sizes, $\log W = \frac{25 - N}{10}$ and $\log W = \frac{25 - 2}{10} = 2.3$ for # 2. 2 is the logarithm of 100 and setting the slide at 3 on the evenly divided scale, we read 2 at the other end of the slide on the lower scale. Hence $W = 2 \times 100 = 200$ lbs. per 1000 feet. Proceeding in a similar manner for # 4, $\frac{25 - 4}{10} = 2.1$ we read 126 on the lower scale, whence the weight of # 4 per 1000 ft. is 126 lbs.

To ascertain circular mils, $\log M = \frac{50.2 - N}{10}$.

For # 2, $\log M = \frac{50.2 - 2}{10} = 4.82$. 4 is the logarithm of 10,000, and setting the slide at 8.2 on the evenly divided scale, read 6.62 at the opposite end on the lower scale of the rule. Hence # 2 has $10{,}000 \times 6.62 = 66{,}200$ cir. mils. Similarly for # 4, $\log M = \frac{50.2 - 4}{10} = 4.62$.

Setting the slide at 6.2 read 4.17. $4.17 \times 10{,}000 = 41{,}700$ c.m.

Edison Gage. — In the development of Edison low-tension mains, and feeders, it soon developed that sizes larger than the largest gage numbers would be very common. Edison therefore established a system of designating conductors by the number of thousands of circular mils of area. Thus a conductor having an area of 100,000 c.m. was called a 100 conductor. Similarly 500,000 c.m. was called 500 and 1,000,000 c.m. was called 1000.

This is perhaps not properly termed a wire gage, as it

applies to stranded cables, made up of a considerable number of wires having numbers in the American Wire Gage. It, however, serves a very useful function in the designation of feeder and main sizes in low-tension networks.

The use of this system has had a tendency to encourage the use of areas of conductors as a means of designation rather than numbers and this limits the use of the wire gage numbers to smaller wires.

The diameter of wires of sizes down to # 12 in the Roebling, Washburn & Moen, Birmingham, and American Wire gages are as follows:

COMPARISON OF WIRE GAGES

No.	Roebling, W. & Moen	American	Stubs Birmingham
6–0	.460	....	....
5–0	.430	....	....
4–0	.393	.460	.454
3–0	.362	.4096	.425
2–0	.331	.3648	.380
0	.307	.3249	.340
1	.283	.2893	.300
2	.263	.2576	.284
3	.244	.2294	.259
4	.225	.2043	.238
5	.207	.1819	.220
6	.192	.1620	.203
7	.177	.1443	.180
8	.162	.1285	.165
9	.148	.1144	.148
10	.135	.1019	.134
11	.120	.0907	.120
12	.105	.0808	.109

Stranded Cables. — In the larger sizes of conductors the rigidity of a single wire is so great that it is necessary that it be subdivided into a number of strands sufficient to give the necessary flexibility for handling economically.

The strands may be arranged in concentric layers about a central core, or they may consist of a "rope-lay" made up by combining several smaller cables having a concentric lay as shown in Fig. 187. The rope lay is not used generally for electrical conductors, its use being limited to extra flexible cables having very small wires.

In a concentric lay cable the smallest number of wires which is used is seven. The space about the core is filled by six conductors since the diameter of the circle passing through their centers is twice the diameter of the wire and the circumference of the circle is 6 d. Likewise the diameter of the third layer is 4 d and 12 conductors fill the space making a 19-conductor cable.

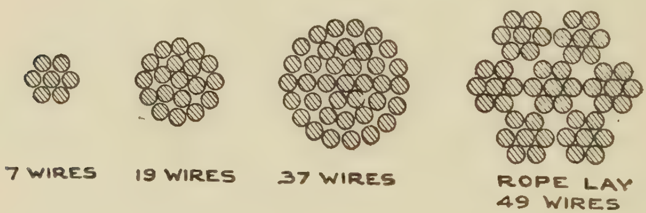


Fig. 187. Cable Stranding.

The diameter of a concentric lay cable is taken as that of the circle circumscribing the outer layer. It is expressed approximately by the formula $D = d(2\,n + 1)$ in which d is the diameter of the individual conductors and n is the number of layers on the core. Therefore in a 19-strand 2-layer cable of wires, having a diameter of .1 inch, the outside diameter is $D = .1\ (2 \times 2 + 1) = .5$ inch. The diameter is about 15 per cent greater than that of a solid wire of equal cross-section.

The pitch of a cable is the ratio of the axial length of one complete turn of a strand to the diameter of the cable. This varies somewhat with different manufacturers and with the size of the cable. It is made as high as practical, however, as

a low pitch requires a greater length of strand to produce a given length of cable. In cables having a pitch of 15.7 the resistance is increased 2 per cent over what it would be if there were no spiraling. The weight is increased by a like percentage also. For a cable having a pitch materially different from the value 15.7 the resistance and weight may be calculated by applying the following correction factor to the values given in the table for stranded cables. The correction factor is

$$1 + .01\left(\frac{493}{P^2} - 2\right).$$

Then if the pitch is 12 the factor is $1 + .01\left(\frac{493}{144} - 2\right) = 1.0142$,

or if the pitch is 20 the factor is $1 + .01\left(\frac{493}{400} - 2\right) = .9926$.

The diameter of the strands of a cable must usually be drawn to a special size in order to make them aggregate the total cross-section. Thus a 7-conductor cable of # 2 A.W.G. which is to have an equivalent area o 66,400 circular mils must be made up of $66{,}400 \times 1.02 = 67{,}700$ circular mils. Each of the seven strands must therefore have an area of 9670 circular mils, which is a little less than # 10 but more than # 9.

Resistance and Conductivity. — The resistance of a conductor to the flow of electrical energy depends: (*a*) upon the metal of which it is made; (*b*) upon the method of manufacture and purity of the metal; and (*c*) upon the temperature at which it carries the electric current.

The various metals which are present in sufficient quantity to be available for use as conductors have resistances which differ very widely. The metals silver, copper, gold and aluminum are the best conductors in the order named. Silver

is 8 per cent better as a conductor than copper, while copper is about 40 per cent better than gold or aluminum. The method of manufacture of a metal has a considerable influence upon its resistance. Copper in the form of castings ordinarily contains so much impurity that its resistance is from 25 per cent to 100 per cent higher than copper, which has been drawn or rolled after refining. The resistance of drawn copper is somewhat affected by annealing after the drawing process, the resistance being slightly reduced by annealing.

The resistance of all metallic conductors varies with the temperature, being increased by an increase in temperature. Carbon affords a notable contrast to metallic conductors in that its resistance decreases with increasing temperature. Conductivity is the reciprocal of resistance, that is, the conductivity of a conductor is $\frac{1}{R}$, R being its resistance.

For purposes of comparison of conductors, conductivity affords a more convenient working basis than resistance, since the higher the conductivity, the better the conductor for purposes of distribution. Copper, being the most common metal in use for conducting purposes, is made the basis of comparison, and is said to have 100 per cent conductivity when its purity and density are such that one foot of copper wire having a diameter of 1 mil (.001 inch) has a resistance of 10.371 ohms at a temperature of 20° C. or 68° F.

Ordinary commercial drawn or rolled copper has a conductivity of 96 per cent to 99.5 per cent of this value and occasionally samples are found having a conductivity of over 100 per cent. It is usual to specify a conductivity of about 98 per cent when selecting cables for heavy currents and important service.

The conductivity, resistance and temperature coefficients of various common metals follow,

RESISTANCE AND CONDUCTIVITY OF VARIOUS METALS

	Per cent conductivity	Resistivity at 20°C., ohms mil-ft.	Temp. coefficient from 20°C. per deg. C.	Temp. coefficient from 32°F. per deg. F.
Silver	108.2	9.53	.00370	.00222
Annealed copper	100	10.37	.00393	.00240
Gold	72.5	14.21	.00350	.00210
Aluminum	62.1	16.66	.00389	.00235
Zinc	27.6	37.34	.00375	.00226
Platinum (annealed)	17.7	56.60	.00236	.00137
Iron	17.6	61.32	.00555	.00347
Nickel	12.9	84.63	.00553	.00345
Tin	12.1	85.62	.00404	.00245
Lead	7.82	125.54	.00380	.00228

Resistivity. — The resistivity of a metal is the resistance of a certain mass of the metal having certain arbitrarily chosen dimensions. Thus it may be expressed as the resistance between two faces of a cubic centimeter of the metal, or of a wire having a diameter of one mil and a length of one foot, or of a wire having a length of one meter and a weight of one gram. These quantities, when fixed for the pure metal, constitute a standard of reference to which any sample of commercial wire may be directly compared by making resistance measurements and reducing them to the equivalent of these standards.

Resistivity is also known as specific resistance, but this term is not a true expression of the character of the quantity and the term is not approved by the best authorities.

Resistivity is usually expressed directly in ohms, while conductivity is more often expressed as a percentage of the annealed copper standard. The resistivity of pure annealed copper at 20° C. or 68° F. is 10.371 ohms per foot of wire 1 mil in diameter, or .15328 ohm per meter of wire weighing one gram, or 31.394 ohms per 1000 feet of a wire weighing one pound per 1000 feet. This was adopted as the Annealed Copper Standard by the International Electrotechnical

Commission in 1913 and is used as the basis of reference for copper and other conductors where resistivity or conductivity is a factor.

In making measurements of resistivity of commercial samples it is possible to make a more accurate determination by the use of the ohms per meter-gram or per mile pound as a standard than by the ohms per mil-foot, since weights may be more accurately determined than diameters in most cases. The resistivity as determined from ohms per meter-gram is termed mass-resistivity, while that derived on the basis of circular mils is known as volume resistivity.

Mass resistivity $= \frac{RW}{L^2}$, in which R is the resistance of the sample, W is its weight and L is its length.

If a length of ten meters of a wire measures .084 ohm and it weighs 185 grams, its resistivity is $\frac{.084 \times 185}{10 \times 10} = .15540$ ohm per meter-gram.

The conductivity of this sample as compared with the annealed copper standard of .15328 ohm (meter-gram) is therefore

$$\frac{.15328}{.15540} = 98.63 \text{ per cent.}$$

The volume resistivity of a wire is $\frac{Rs}{L}$ in which s is the area of cross-section in circular mils.

If a wire having a length $L = 10$ feet, and a cross-section s of 4110 circular mils is found to have a resistance of .0257 ohm at 20° C., its resistivity is

$$\frac{.0257 \times 4110}{10} = 10.512 \text{ ohms (mil-foot).}$$

The conductivity of the sample as compared with the annealed copper standard of 10.371 ohms (mil-foot) is therefore

$$\frac{10.371}{10.512} = 98.65 \text{ per cent.}$$

Copper. — The commercial distribution of electricity is largely dependent upon the existence of a metal of low resistance to the passage of electricity, high resistance to the corrosive action of moisture in the atmosphere and existing in such quantities as to permit investments to be made in conductors which are within economical limits. Such a metal is copper. It has a density of 8.9 grams per cubic centimeter or 555 lbs. per cubic foot. It melts at 1081° C. or 1981° F. and boils at 2310° C. or 4190° F., giving off a greenish flame. In the molten state it readily absorbs oxygen, hydrogen, carbon dioxide, or carbon monoxide, and when the cooling metal drives off these gases, these are likely to be occluded, thus forming so-called blow holes in the finished casting.

The electrical conductivity of the metal varies widely according to the impurities contained in it. It is therefore classified for commercial purposes into three grades known as electrolytic, lake and casting copper. The first is the product of refinement of cast copper by electrolytic processes and is about 99.9 per cent pure. Lake copper is made by melting nuggets of the native metal into bars. Casting copper is that derived from smelting the ores and necessarily contains considerable impurities. It is used chiefly for mechanical purposes. This grade of copper is also derived from impure solutions electrolytically and from processes yielding copper as a by-product. The better grades of casting copper are about 99 per cent pure.

Lake copper is mined in the northern peninsula of Michigan in a rock ore which is crushed in stamp mills, concentrated

and melted into bars. This is the only source of this kind of copper.

Temperature Coefficient. — The variation of resistance of a conductor with rise or fall of temperature follows a definite law for any given metal which may be expressed in the form

$$R_t = R_{t_1}[1 + a_{t_1}(t - t_1)],$$

in which R_{t_1} is the known resistance at $t_1°$ C.

a_{t_1} is a constant for the rate of increase when starting at $t_1°$ C., t is the temperature at which it is desired to know the value of R_t. Thus if it is known that a conductor has a certain resistance at a temperature of 20° C. its resistance at 50° C. may be readily determined by this rule if the values of a_t have been experimentally established for various temperatures within usual working limits.

The value of a_t, the temperature coefficient, varies with the temperature at the starting point. It is higher for resistances measured initially at 0° than for those measured at 20° or 30°. It also varies with the conductivity of the metal, as shown in the following table.

Temperature Coefficients of Copper for Different Initial Temperatures (Centigrade) and Different Conductivities

Per cent conductivity	a_0	a_{15}	a_{20}	a_{25}	a_{30}	a_{50}
95	.00403	.00380	.00373	.00367	.00360	.00336
96	.00408	.00385	.00377	.00370	.00364	.00339
97	.00413	.00389	.00381	.00374	.00367	.00342
97.3	.00414	.00390	.00382	.00375	.00368	.00343
98	.00417	.00393	.00385	.00378	.00371	.00345
99	.00422	.00397	.00389	.00382	.00374	.00348
100	.00427	.00401	.00393	.00385	.00378	.00352
101	.00431	.00405	.00397	.00389	.00382	.00355

In the case of annealed copper the values of a_t have been determined with great care by investigators of this country

and Europe and the figures appearing in the above table are the standard values as published by the U. S. Bureau of Standards.

The values given for a conductivity of 100 per cent may be used for annealed copper in the form of so-called " soft drawn " wire, or the windings of transformers and electrical machinery.

Hard drawn wire has an average conductivity of 97.3 per cent and the values given for that conductivity in the table should be used for such wire.

Illustrations.

With an annealed copper conductor having a resistance of .2 ohm at 20° C. the resistance at 45° C. would be

$$R = .2\,[1 + .00393\,(45 - 20)] = .2\,(1.0982) = .2196 \text{ ohm.}$$

With hard copper having a resistance of .2 ohm for a certain length at 20° C. the resistance at 45° C. is

$$R = .2\,[1 + .00382\,(45 - 20)] = .2\,(1.0955) = .2191 \text{ ohm.}$$

The average temperature of a cable or transformer coil may be calculated from measurements of its resistance at normal temperature and again after it has had its temperature increased by the passage of current by the use of the foregoing formula.

For example, a cable was found to measure .5 ohm with average manhole temperatures of 15° C. (59° F.) and .55 ohm after a 6-hour run under load. What was its average temperature at the end of the run?

In the formula, $R = .55$, $R_t = .5$ and a_t is .00393.
Whence,

$$.55 = .5\,[1 + .00401\,(t - 15)] = .5 + .002005\,(t - 15),$$

$$\frac{.55 - .5}{.002005} = t - 15,$$

$$t = \frac{.05}{.002005} + 15 = 40° \text{ C.}$$

Again, if a coil has a resistance of 10 ohms at 20° C. (68° F.) and a resistance of 11.5 ohms after carrying a load, what is its temperature?

$$11.5 = 10\,[1 + .00393\,(t - 20)] = 10 + .0393\,(t - 20),$$

$$\frac{11.5 - 10}{.0393} + 20 = t = 58.1^\circ \text{ C.}$$

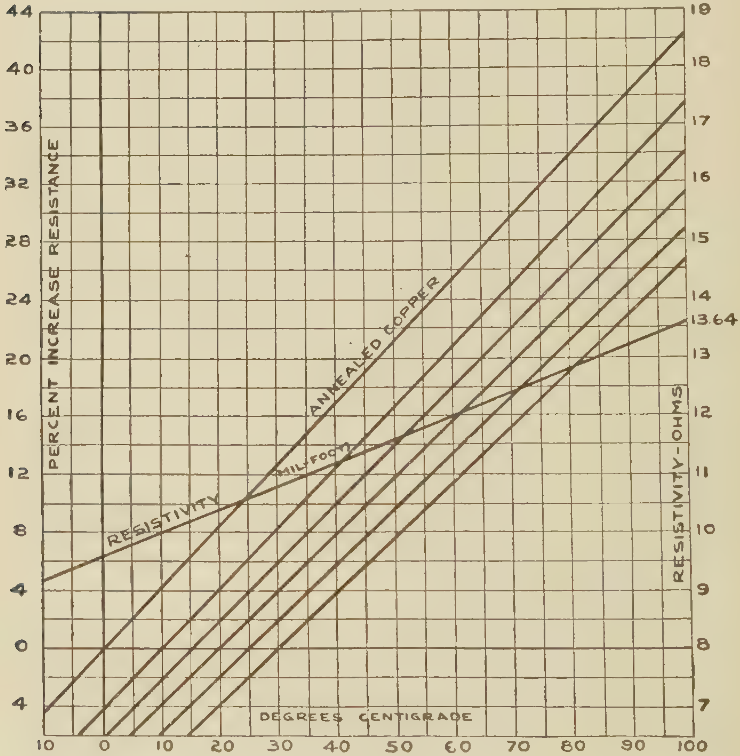


FIG. 188.

Calculations of resistances at various temperatures or of temperatures corresponding to different resistances may be facilitated by the use of a diagram such as that in Fig. 188, which shows the percentage of increase of resistance at all

temperatures up to 100° C. from 0, 10, 15, 20, 25 and 30 degrees points of reference, for annealed copper. It also shows the change in resistivity (mil-foot) as the temperature varies.

Referring to the foregoing cases which were calculated by the use of the formula, the solutions are made by the use of the diagram as follows:

Given a conductor with a resistance of .2 ohm at 20° C., what is its resistance at 45° C.?

Referring to the diagram, the line crossing the line of 0 percentage at 20° crosses the 45° line at 9.8 per cent. Hence

PROPERTIES OF ANNEALED SOLID COPPER WIRE

Size, A.W.G.	Diameter in mils	Cross-section		Weight per 1000 ft.	Per 1000 ft. weather-proof	Ohms per 1000 ft.	
		Circular mils	Square mils			20° C.	50° C.
0000	460.0	211,600	.1662	640.5	741	.04901	.05482
000	409.6	167,800	.1318	570.9	598	.06180	.06912
00	364.8	133,100	.1045	402.8	485	.07783	.08716
0	324.9	105,500	.08289	319.5	382	.1002	.1099
1	289.3	83,690	.06573	253.3	312	.1264	.1386
2	257.6	66,370	.06213	200.9	254	.1563	.1748
3	229.4	52,640	.04134	159.3	199	.1970	.2204
4	204.3	41,740	.03278	126.4	163	.2485	.2779
5	181.9	33,100	.02600	100.2	132	.3133	.3504
6	162.0	26,250	.02062	79.46	109	.3951	.4418
7	144.3	20,820	.01635	63.02	88	.4982	.5572
8	128.5	16,510	.01297	49.98	74	.6282	.7025
9	114.4	13,090	.01028	39.63	60	.7921	.8860
10	101.9	10,380	.008155	31.43	50	.9989	1.117
11	90.74	8,234	.006467	24.92	42	1.260	1.409
12	80.81	6,530	.005129	19.77	34	1.588	1.776
13	71.96	5,178	.004067	15.68	...	2.003	2.240
14	64.08	4,107	.003225	12.43	24	2.525	2.824
15	57.07	3,257	.002558	9.858	...	3.184	3.562
16	50.82	2,583	.002028	7.818	19	4.015	4.491

the increase in resistance is 9.8 per cent and the resistance of the conductor at 45° is $1.098 \times .2 = .2196$ ohm, as found by calculation.

Given a cable having a resistance of .5 ohm at 15° and of .55 ohm after a run under load, what is its average temperature?

The increase in resistance is .05 ohm or 10 per cent. Following the line which crosses the 0 line at 15° until it reaches 10 per cent the temperature is seen to be 40°, as found by calculation.

PROPERTIES OF ANNEALED STRANDED COPPER CABLES

Size, A.W.G.	Circular mils	Weight per 1000 ft.	Standard strands			Ohms per 1000 ft.	
			Number of wires	Diameter of wires in mils	Outside diameter in mils	25° C.	65° C.
....	2,000,000	6,180	127	125.5	1631	.00539	.00623
....	1,500,000	4,630	91	128.4	1412	.00719	.00839
....	1,000,000	3,090	61	128.0	1152	.0108	.0125
....	750,000	2,320	61	110.9	998	.0144	.0166
....	600,000	1,850	61	99.2	893	.0180	.0208
....	500,000	1,540	37	116.2	814	.0216	.0249
....	400,000	1,240	37	104.0	728	.0270	.0311
....	350,000	1,080	37	97.3	681	.0308	.0356
....	300,000	926	37	90.0	630	.0360	.0415
....	250,000	772	37	82.2	575	.0432	.0498
0000	....	653	19	105.5	528	.0510	.0589
000	....	518	19	94.0	470	.0643	.0742
00	....	411	19	83.7	418	.0811	.0936
0	....	326	19	74.5	373	.102	.118
1	....	258	19	66.4	332	.129	.149
2	....	205	7	97.4	292	.163	.188
3	....	163	7	86.7	260	.205	.237
4	....	129	7	77.2	232	.258	.298
5	....	102	7	68.8	206	.326	.376
6	....	81	7	61.2	184	.411	.475

In a similar way for any ordinary initial temperature resistances may be determined by following the line which crosses the zero line at the initial temperature in question.

The diagram may be used for aluminum as well as copper

as the temperature coefficients of these two metals are very nearly equal.

With a diagram drawn to a larger scale quite accurate results can be secured graphically with a minimum of calculation.

The size, weight and resistance of the sizes of solid and stranded wire in general use in distribution are given in the accompanying tables.

Mechanical Properties of Copper. — The tensile strength of copper varies with its physical condition. In the form of annealed wire it breaks at 32,000 to 37,000 pounds per square inch in the larger sizes and at 35,000 to 40,000 pounds in the smaller sizes. Hard drawn wire has a strength of about 50,000 pounds per square inch in the large sizes and 65,000 pounds per square inch in the smaller sizes. Cast copper ranges from 20,000 to 30,000 pounds per square inch.

The strength of hard drawn wire is reduced to that of annealed wire by subjecting it to a temperature of about 250° C. The strength reduction proceeds rapidly between 150° and 225° C. For this reason the soldering of joints reduces the strength of the wire near the joint to that of annealed wire. The use of a mechanical form of joint is therefore usual where hard drawn wires are spliced or tapped at points where they are under strain which is too great for annealed wire.

The process of cold drawing hardens the wire and the more it is reduced in section the harder it becomes. The smaller sizes are the stronger because a larger portion of the metal is in the hardened state.

Annealed copper is quite ductile and stretches appreciably under stresses which are considerably below its breaking point. It elongates about 35 per cent over its initial length before breaking. Hard drawn copper is, however, much less subject to elongation. In the larger sizes it takes a permanent

set of about 4 per cent, but the smaller sizes are elongated only 1 to 2 per cent. The elongation of copper wires affords a material relief to overhead wires which are loaded with sleet and contracted by low temperatures, since the tensile strains are relieved by the elongation of the wire.

The elongation of concentric lay cables is somewhat greater than that of solid wires, since the stress tends to cause a re-adjustment of the pitch of the cable. The strength of such cables is probably not over 90 per cent of that of an equivalent solid conductor.

The elongation of wires was discussed in a paper by F. O. Blackwell, read before the International Electrotechnical Congress in 1904. The experiments therein described showed that copper wire stretches gradually when kept under strains which are considerably below the elastic limit. When the stress is removed and reapplied the wire behaves as if it had been hardened by stretching. It requires a greater stress to produce a given elongation and the elastic limit is increased.

The curves in Fig. 189 show the manner in which copper wire in various conditions of hardness elongates under stress. Curve A shows that annealed wire .168 inch in diameter begins to elongate rapidly under a load of 10,000 pounds per square inch. Medium hard drawn trolley wire begins to stretch rapidly between 35,000 and 40,000 pounds per square inch, while a # 10 hard drawn telephone wire does not stretch until 60,000 pounds per square inch has been exceeded.

In the case of annealed wire the stretching process is slow enough to permit additional strain to be applied. The limits of the curve are much too small to carry this out to the breaking point, as it does not break until an elongation of about 35 per cent has been reached. With hard drawn wire the elongation proceeds too rapidly after the elastic limit has been passed to permit much increase in the stress to be made.

It is evident from these curves that the elastic limit of copper is not a definite quantity, but varies with the degree of hardness of the metal and to some extent with the rate at which the application of load is increased. It is usually considered that loads applied in overhead construction should not ex-

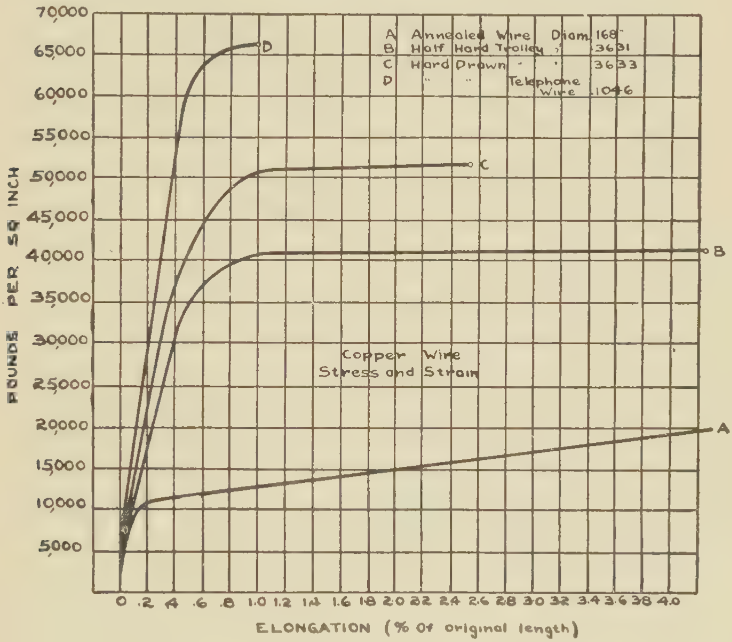


Fig. 189.

ceed 50 per cent of the ultimate breaking strength, under the most severe conditions of loading.

The breaking strengths of wires of # 10 to # 0000 as required by the specifications of the American Society for Testing Materials appear in the following table.

STRENGTH OF COPPER WIRES

Gage No., A.W.G.	Diameter in mils	Breaking load (lbs. per sq. in.)		
		Annealed	Medium	Hard
0000	460	5,650	6,980	8,310
000	410	4,480	5,680	6,590
00	365	3,560	4,620	5,220
0	325	2,820	3,730	4,560
1	289	2,240	3,020	3,740
2	258	1,870	2,450	3,120
3	229	1,400	1,980	2,480
4	204	1,115	1,590	1,960
5	182	885	1,260	1,560
6	162	700	1,010	1,240
8	128	60	646	790
10	102	00	410	490

Aluminum. — The use of aluminum in transmission practice has been sufficiently general to make its properties of importance to electrical engineers. It has the very low density of 2.7 grains per cubic centimeter, as compared with 8.9 for copper, and this is the principal reason for its use. It is ductile and may be hard drawn and treated otherwise much the same as copper.

Aluminum melts at 658° C. and boils at 1800° C. Like copper it is protected by the thin coating of oxide which forms upon it and prevents further corrosion under atmospheric conditions. This protective coating forms so quickly that it is not possible to solder aluminum in the ordinary manner. Its electrical conductivity is affected by its purity as is copper, and it has a somewhat lower conductivity when hard drawn than in the annealed state. The impurities are usually silicon and iron.

The mass resistivity of aluminum is .0764 ohm (meter-gram) at 20° C. The conductivity is 61 per cent of that of

annealed copper, and the density being $\frac{2.7}{8.9} = 30.33$ per cent of that of copper, it follows that an aluminum conductor having the same resistance per 1000 feet as a copper conductor has a weight of $\frac{30.33}{61} = .497$ of the copper conductor.

The temperature coefficient varies as it does with copper according to the temperature of reference, but it has an average value of .0039 per degree C. from and at 20° C.

The size, weight and resistance of aluminum wires are as follows:

PROPERTIES OF STRANDED ALUMINUM CABLES

No. B.&S.	Bare diam., mils	Area, circular mils	Weight				Resistance at 68° F.	
			Per 1000 ft.	Per mile	Per 1000 ft., weather-proof	Bare feet per lb.	Per 1000 ft.	Per mile
..	1.15	1,000,000	920	4858	1408	1.087	.01695	.0895
...	1.00	750,000	690	3645	1067	1.45	.0226	.1193
....	.81	500,000	460	2430	740	2.04	.033	.179
....	.73	400,000	368	1944	567	2.72	.0424	.224
....	.68	350,000	322	1701	502	3.11	.0484	.256
....	.63	300,000	276	1458	436	3.62	.0565	.298
....	.58	250,000	230	1215	375	4.35	.0678	.358
4–0	.54	211,600	195	1028	280	5.73	.08	.423
3–0	.47	167,800	154	816	232	6.48	.101	.533
2–0	.42	133,100	122	647	192	8.16	.127	.673
0	.37	105,500	97.1	513	155	10.3	.160	.847
1	.33	83,690	77	407	132	13	.202	1.069
2	.30	66,270	61	323	108	16.4	.255	1.35
3	.26	52,630	48.5	256	88	20.6	.322	1.70
4	.23	41,740	38.5	203	72	26	.406	2.144

The tensile strength varies with the hardness and method of treatment during manufacture. Castings have a strength under tension of 12,000 to 14,000 pounds per square inch. Soft wire has a strength of 14,000 pounds per square inch in

the larger sizes of wire and as high as 33,000 pounds per square inch in the small sizes. Hard drawn wire in sizes ordinarily used in overhead lines has a strength of 23,000 to 27,000 pounds per square inch. This is used for overhead

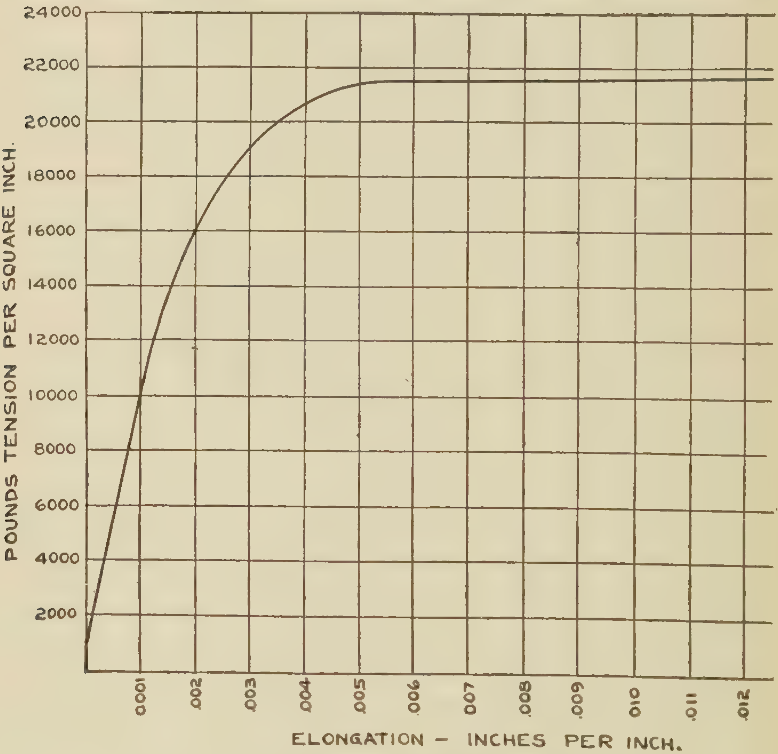


Fig. 190. Aluminum.

lines exclusively. The coefficient of expansion with variation of temperature is approximately .0000231 per degree C. at temperatures between 0° and 100° C.

The elongation of aluminum under the stress of overhead construction is more uniform than that of copper, it being appreciable at loads considerably below the safe working stress of 50 per cent of the ultimate breaking strength. The rate of

elongation is shown very well in the diagram, Fig. 190, for a # 6 A.W.G. conductor. In hard drawn wires the total elongation at rupture is from 2 to 4 per cent.

Copper Clad Steel. — Steel wire with copper coating has certain advantages for use where great strength is required without a high conductivity. This wire is made up in rods with the proper proportion of steel and copper and then drawn into wire, having an electrical conductivity of 30 to 50 per cent of that of a copper wire of equal cross-section. The wire is annealed at intervals between successive reductions and may be had as soft, medium or hard wire.

The coefficient of linear expansion is .0000129 per degree C. and the density is 8.2 grams per cu. cm.

The tensile strength depends somewhat upon the steel forming the core, but usually varies from 80,000 to 100,000 pounds per square inch. The elongation is very similar to that of hard drawn copper.

Steel Wire and Cables. — The use of steel wire and cable for electrical distribution is general where great strength is required and where low first cost to reach a small neighboring community is necessary. It is also used in great quantities for guying and cable suspension purposes.

The resistivity of iron and steel varies widely with their composition. In general it is about six times that of copper for wrought iron and about eight times that of copper for steel.

The temperature coefficient of resistance of pure iron has a mean value of about .000635 per degree C. between 0° and 100° C. In the form of carbon steel this varies from .00025 to .00042, depending upon the temper. The former figure applies to a light yellow temper, and the latter to soft dark blue steel.

The density of iron is 7.86 grams per cubic centimeter and that of steel about 2 per cent greater. Iron weighs 480 pounds per cubic foot and steel about 490 pounds.

The tensile strength depends upon composition as well as upon the process of manufacture. It varies from 50,000 pounds per square inch for soft pure iron to 180,000 pounds or more in hard drawn steel wire.

The elongation before rupture is about 10 per cent for iron wire and elastic limit is reached at about 50 per cent of the breaking point. The coefficient of linear expansion is about .0000064 per degree F.

Steel wire is used largely in the form of stranded cable for guying purposes, or as ground wire on transmission lines, seven-strand cable being usual. In the case of branch lines from high voltage systems supplying a small load small single conductor wire is often employed, as the current is small and the investment must be kept as low as possible.

Current Carrying Capacity. — The flow of electricity along a conductor is accompanied by a loss of energy which is proportional to the square of the current in amperes and the resistance of the circuit. This may be written watts loss = C^2R, C being the current flowing and R the resistance of the circuit. The loss in a circuit having a resistance of .1 ohm when it is carrying a load of 100 amperes is $100 \times 100 \times .1 = 1000$ watts. The energy absorbed by the resistance of the circuit is dissipated in the form of heat, which raises the temperature of the conductor in proportion to the energy absorbed and to the heat radiated. The maximum current carrying capacity of a conductor of given size is therefore dependent upon whether it is installed in open air, in conduit or underground. The character of the insulation is also a factor, since certain insulations may be safely operated at higher temperatures than others. Weatherproof insulation

may be safely operated at higher temperatures than rubber, while bare wire may be operated at much higher temperatures than any of the usual forms of insulation will withstand.

If the maximum allowable temperature is known for any class of insulation the maximum current which the circuit may carry under the given condition may be calculated from the following formula:

$C = A\sqrt{\frac{TD^3}{1.8\,r}}$, in which T is the rise in temperature in degrees F., D is the diameter of the conductor in inches (not including insulation), r is the resistance per mil-foot at the final temperature, and A is a constant which varies with the character of the insulation and method of installation as follows:

Bare wire in open air	A is 1100
Bare wire indoors	A is 600
Rubber-covered wire indoors	A is 500
Underground cable, rubber insulation, single conductor	A is 500
Underground cable, paper or cloth, single conductor	A is 550
Underground cable, rubber insulation, three conductor	A is 380
Underground cable, paper or cloth, three conductor	A is 330

The values of r, the resistivity, at various temperatures, are shown in the curve in Fig. 176.

With a circuit of # 0 bare copper wire in open air, in which it is permissible to allow the temperature to rise from 70° to 120° F., D is .325, T is 50, r is 11.6 and A is 1100. The current which would produce this rise in temperature is $C = 1100\sqrt{\frac{50 \times (.325)^3}{1.8 \times 11.6}} = 310$ amperes. The same wire in-

doors could be loaded to $\frac{600}{1100} \times 310 = 170$ amperes, or in an underground single-conductor paper cable to $\frac{550}{1100} \times 310 =$ 155 amperes.

CURRENT CARRYING CAPACITY OF COPPER CONDUCTORS

Size, A.W.G.	Rubber	Weatherproof	Size, A.W.G.	Rubber	Weatherproof
14	15	20	00	150	225
12	20	25	000	175	275
10	25	30	0,000	225	325
8	35	50	250,000	235	350
6	50	70	300,000	275	400
5	55	80	350,000	300	450
4	70	90	400,000	325	500
3	80	100	500,000	400	600
2	90	125	750,000	525	800
1	100	150	1,000,000	650	1000
0	125	200	1,500,000	850	1360
....	....	....	2,000,000	1050	1670

The use of such a formula is of value chiefly for special cases, as it is more convenient to have tables showing the current carrying capacity of the various sizes of conductors under different conditions for ordinary use.

The safe carrying capacity of the sizes of conductors commonly used in distribution work is given in the accompanying table. These are the values permitted by the National Electric Code in interior work and they may be exceeded somewhat in outdoor or underground construction.

Voltage Drop. — The transmission of electricity over a conductor is accompanied by a loss of pressure due to its resistance. The scientist Ohm discovered that this loss is $E = C \times R$, when C is the current flowing and R the resistance of the conductor, and it is called Ohm's law. It is strictly true only for direct-current circuits.

A simple electric circuit is composed of two elements, the conductors leading to the lamp or motor and the receiving device itself. The current passing through the circuit is the same in both elements, but the resistances of the conductors and the lamp are different, and the fall of pressure in each part as the current passes through the circuit is directly proportional to these resistances.

The function of the conductor being to convey the supply of electricity from its source to the consuming device, it is desirable that as little pressure be absorbed by the resistance of the conductor as possible.

Calculation of Direct Current Circuits. — The problem of designing a circuit is therefore one of determining what size of conductor should be used to limit the loss of voltage to a specified amount, when the distance and current to be carried are known.

The resistance of a mil-foot of copper at 68° F. being about 10.4 ohms, that of a conductor D feet long and M circular mils in area is $R = \frac{D \times 10.4}{M}$. The drop with current C is therefore $E = CR = \frac{C \times D \times 10.4}{M}$ or $M = \frac{C \times D \times 10.4}{E}$. If both conductors are of the same size the total drop is $E = \frac{2\,D \times C \times 10.4}{M}$. If they are not of the same size, the drop in the different sizes must be figured separately and added together.

For example, assume that a two-wire circuit is to carry a load of 100 amperes at a distance of 300 feet with a drop of five volts, what size of conductor must be used?

$$M = \frac{2\,D \times C \times 10.4}{E} = \frac{2 \times 300 \times 100 \times 10.4}{5} = 124{,}800 \text{ c.m.},$$

which is found by reference to the wire table to be approximately the section of # 00, which should be used.

If a circuit of # 4/0 wire is to carry 100 amperes 500 feet, what will be the voltage drop? In the wire table # 4/0 has an area of 211,600 circular mils, and $E = \frac{2 \times 500 \times 100 \times 10.4}{211,600}$ = 4.9 volts.

The calculation of such problems can be simplified where the size of the circuit is already fixed by the use of the values of resistance per 1000 feet given in the wire table. For instance, in the case of the 500-foot circuit of # 4/0 wire, the resistance per 1000 feet being .0489 ohm, and the circuit being .5 thousand feet long, $E = C \times R = 100 \times .0489 \times .5 \times 2 =$ 4.9 volts. This operation involves only multiplication, and the calculation is therefore somewhat more simple.

The use of a table is not always convenient, but when this method is used regularly, it becomes an easy matter to memorize the resistance of a few principal sizes, from which it is easy to find the odd sizes by applying the law of the American wire gauge table, as hereinbefore described.

Three-wire Circuits. — In making calculations for a three-wire Edison circuit, separate computations must be made for each conductor if the load is appreciably unbalanced.

For example, if a circuit having two # 4/0 outers and a # 0 neutral 1000 feet long carries a load of 150 amperes on the positive side and 110 amperes on the negative side, the drop will be found as follows:

Resistance of 1000 feet of 4/0 = .05 ohm and that of # 0 = .1 ohm.

$E = CR = 150 \times 0.5 = 7.5$ volts on positive wire.
$E = CR = 110 \times .05 = 5.5$ volts on negative wire.
$E = CR = 40 \times .1 = 4$ volts on neutral wire.

The neutral wire drop is added to the drop on the heavy side and subtracted from that on the lighter side, making

the drop 7.5 + 4 = 11.5 volts on the heavy side and 5.5 − 4 = 1.5 volts on the other side. If the pressure of the supply is 120 volts on each side, the pressure at the other end will be 120 less 11.5 = 108.5 on the positive side, and 120 less 1.5 = 118.5 on the negative side. These relations are shown graphically in Fig. 191 (*a*).

This example illustrates the importance of keeping three-wire mains approximately balanced. It also indicates the

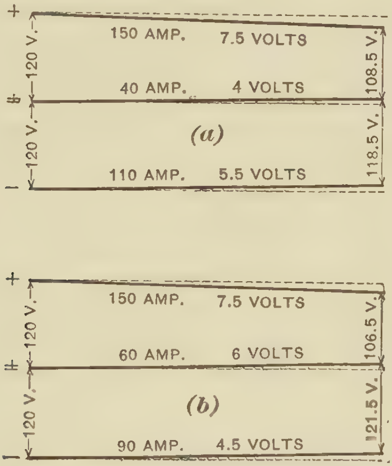


Fig. 191. Voltage Drop in Three-wire Circuit.

necessity of having the neutral of ample size so as not to emphasize unbalanced conditions when they exist. In this case, if the neutral had been of 4/0 the drop on it would have been 2 volts; the pressure on the positive side at the far end would have been 110.5 volts, with 116.5 on the negative.

When the conditions are such that the drop on the neutral conductor exceeds that on the lighter loaded side, the pressure on the lighter side at the far end is higher than the pressure at the source of supply. This condition is illustrated in Fig. 191 (*b*), and is one which is sometimes found in practice

on branches where the load consists of a few two-wire consumers whose hours of use are so irregular that they cannot be arranged to balance each other at all times.

In this case the outsides are # 4/0 and the neutral # 0.

The drop on the positive at 150 amperes is 7.5 volts.

The drop on the negative at 90 amperes is 4.5 volts.

The drop on the neutral at 60 amperes is 6 volts.

With 120 volts at the point of supply the pressure at the far end is 120 less $(7.5 + 6)$ volts $= 106.5$ volts on the positive side, while on the negative side it is 120 less 4.5 volts plus 6 volts $= 121.5$ volts, or 1.5 volts higher than at the point of supply.

CHAPTER XVI

ALTERNATING-CURRENT CIRCUITS

In an alternating-current circuit voltage drop is caused by the combined effect of: (*a*) *resistance*, (*b*) *inductance*, (*c*) *capacity*, and in very large conductors (*d*) *skin effect*.

The component of drop due to resistance is directly opposed to the current flowing in the circuit, and as in direct-current circuits is $E = CR$.

Inductance. — The component of drop due to inductance is a counter electromotive force set up in the circuit by the current flowing through it. The magnetic field of the circuit, reversing with each alternation, induces an electromotive force in it, which lags a quarter cycle behind the current wave. The resistance drop being directly opposed to the current and the reactance drop being a quarter cycle behind it, their relation may be represented by two sides of a right-angled triangle, as in Fig. 192. The line OC represents the resistance drop in 1000 feet of # 6 wire, and the line CD represents the reactance drop in the same length of wire. The resultant OD of these two influences is called the *impedance*. The inductance of an electric current varies with the frequency of the current flowing in the circuit and with the number of lines of force linked with the circuit for each ampere of current flowing in it. The reactance of a given circuit is therefore more when it

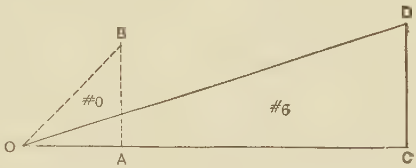


Fig. 192. Resistance and Reactance of No. 6 and No. 0.

carries current at 60 cycles than at 25 cycles. Similarly, inductance is increased by the separation of the conductors of a circuit or by the introduction of iron into the magnetic field, since either of these increases the number of lines of force linked by the circuit.

For this reason if alternating-current circuits are to be installed in iron pipe, all conductors of the circuit must be carried in the same pipe so that the entire magnetic field will be within the pipe.

Calculation of Inductance. — The inductance of a single-phase circuit is $X = \frac{2\,d \times 6.28 \times L \times f}{1000}$ ohms, in which L is the coefficient of self-induction in millihenrys per 1000 feet of wire, f is the frequency and d is the length in thousands of feet.

The coefficient of self-induction of parallel wires of non-magnetic metal, strung in open air and without iron in the magnetic field, may be calculated from the formula

$$L = .14 \log \frac{D - r}{r} + .0152 \text{ millihenry per 1000 feet of wire,}$$

in which D is the distance between centers of the conductors and r is the radius of the conductor.

For a circuit of # 0 wire strung 12 inches apart,

$$L = .14 \log \frac{12 - .162}{.162} + .0152 = .277 \text{ millihenry.}$$

At 60 cycles, the inductance is

$$X = \frac{6.28 \times 60\,L}{1000} = .377\,L = .1043 \text{ ohm per 1000 feet of wire.}$$

At 25 cycles,

$$X = \frac{6.28 \times 25\,L}{1000} = .157\,L = .0434 \text{ ohm per 1000 feet of wire}$$

The reactance at any other frequency is in direct proportion to the ratio of the frequencies.

From the formula for self-induction it is apparent that the effect of the separation of the wires does not vary directly with the distance of separation.

For instance, when D is 2 inches the value of $\frac{D-r}{r}$ for # 0 wire is $\frac{2-.162}{.162} = 11.3$ and the value of the logarithm is 1.054. At 12 inches, $\frac{D-r}{r}$ is 73.2 and the logarithm is 1.87.

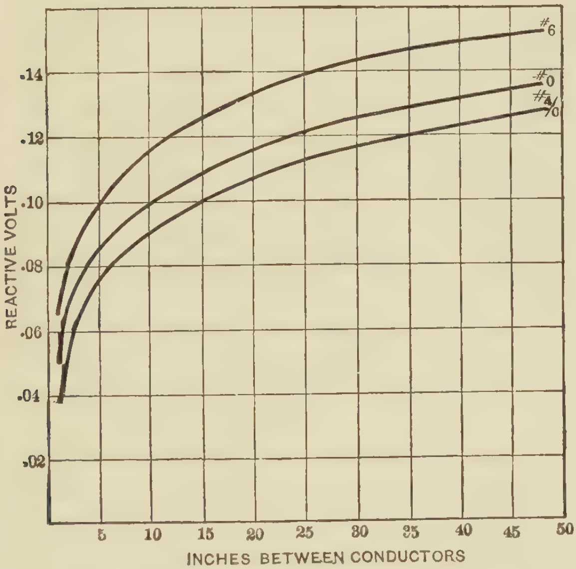


Fig. 193. Relation of Reactance to Separation of Conductors.

At 2 in. $L = .14 \times 1.054 + .0152 = .165$.
At 12 in. $L = .14 \times 1.87 + .0152 = .277$.

The inductance is decreased 40 per cent, while the distance has been increased to six times its former value.

The rate of change of the inductance as the distance between centers is varied is shown for a few principal sizes of conductor by the curves in Fig. 193. These are based on the values given in the following table.

INDUCTANCE PER 1000 FEET OF CONDUCTOR AT 60 CYCLES

Size	Volts per ampere						Resistance at 68° F.
	Distance between centers						
	¾ in.	1 in.	2 in.	3 in.	6 in.	12 in.	
1,000,000	....	....	....	....	.063	.0784	.01035
500,000	....	....	....	....	.071	.0864	.0207
350,000	....	....	....	....	.0746	.0905	.0296
0000	.0328	.0394	.0553	.0646	.0805	.0964	.0489
000	.0355	.0421	.058	.067	.0832	.0991	.0617
00	.0381	.0447	.060	.070	.0858	.1017	.0778
0	.0408	.0474	.0633	.0726	.0885	.1043	.0981
1	.0435	.0501	.0659	.0752	.0911	.107	.1237
2	.0461	.0527	.0686	.0779	.0938	.1097	.156
4	.0514	.0580	.0739	.0832	.0991	.1150	.248
6	.0567	.0633	.0792	.0885	.1044	.1203	.394
8	.0621	.0687	.0845	.0938	.1097	.1256	.627
10	.0674	.074	.0898	.0991	.1151	.1309	.997

Size	18 in.	24 in.	36 in.	48 in.	60 in.	72 in.
1,000,000	.0877	.0943	.1036	.1102	.1153	.1194
500,000	.0957	.1023	.1116	.1182	.1233	.1274
350,000	.0998	.1064	.1157	.1223	.1274	.1316
0000	.1057	.1123	.1216	.1282	.1333	.1374
000	.1084	.1150	.1242	.1308	.1360	.1401
00	.1110	.1176	.1269	.1335	.1386	.1427
0	.1136	.1202	.1295	.1361	.1412	.1454
1	.1163	.1229	.1322	.1388	.1439	.1481
2	.1190	.1256	.1348	.1414	.1466	.1507
4	.1243	.1309	.1402	.1468	.1519	.1561
6	.1296	.1362	.1455	.1521	.1572	.1613
8	.1349	.1415	.1508	.1574	.1625	.1667
10	.1402	.1468	.1561	.1627	.1678	.1720

It is to be noted that the reactance increases rapidly as the separation is increased up to six inches and then less and less rapidly as the separation is increased.

This is a favorable condition for overhead transmission lines operating at high voltages which require large separations between opposite polarities.

It is also fortunate that in underground cables distributing heavy low-potential currents the conductors can be brought close together inside of one lead sheath, thus minimizing the inductive component of line drop.

The calculation of the inductive drop is not convenient when logarithms are not readily available and is simplified by the use of the values given in the table, which gives the reactance in volts per ampere for 1000 feet of conductors for the distances of separation and sizes of wire commonly used in transmission and distribution work.

For example, assuming a single-phase circuit 10,000 feet long operating at 60 cycles and carrying a load of 100 amperes, with # 0 wires 12 inches part, what are the values of the inductive and ohmic components of the impedance?

The reactance per 1000 feet per ampere for # 0 wire 12 inches apart is $X = .1043$. The resistance from the table is .098 ohm per 1000 feet. The inductive component of the impedance of the circuit is

$$X = 2\,d \times C \times .1043 = 2 \times 10 \times 100 \times .1043 = 208 \text{ volts.}$$

The ohmic component is $R = 2 \times 10 \times 100 \times .098 = 196$ volts.

The impedance drop of the circuit is $\sqrt{(208)^2 + (196)^2} =$ 286 volts.

The length of the line OA in Fig. 192 is proportional to the resistance component, that of AB represents the inductive component and OB the resultant of the two. If the circuit were of two # 6 wires the resistance component would be

788 volts, the inductive component 240 volts, and the impedance drop would be $\sqrt{(788)^2 + (240)^2} = 824$ volts.

This condition is represented by *OC* and *CD* in Fig. 192. It will be seen from these examples that the inductive component of drop in a # 6 wire is only about 2 per cent greater than that of the # 0 circuit, although its resistance is nearly four times that of the # 0 circuit. It is further apparent that the ratio of resistance to inductance decreases greatly as the size of wire is increased. On this account increasing the area of alternating current conductors for the purpose of reducing the pressure drop becomes less effective after the size is increased above the point where the resistance is about equal to the inductance. At 60 cycles this is at about # 0 for overhead circuits, and at 350,000 to 500,000 c.m. for underground cables. At 25 cycles # 0000 to 250,000 c.m. may be used for overhead lines, and sizes up to 1,000,000 c.m. are effective in underground cables. For instance, in the 10,000 feet of # 0 circuit above referred to, the ohmic drop is 196 volts and the inductive component is 208 volts at 100 amperes. If this circuit were required to carry 200 amperes it could be replaced by 4/0 cable or supplemented by the addition of another circuit of # 0. If a 4/0 circuit were substituted, the ohmic drop would be 196 volts as before, but the inductive drop would be 384 volts. With two # 0 circuits the drop would remain the same, 196 volts ohmic and 208 volts inductive.

Where the drop can be compensated for properly, or where the circuit is so short that the increased drop is negligible, the larger sizes may be used, but where line drop is the limiting feature, two or more circuits of the smaller wire are preferable.

Resistance and Inductance Factors. — The *resistance factor* of a circuit is the ratio of its resistance to its impedance.

Likewise the *inductance factor* is the ratio of the inductance to the impedance.

In the # 0 circuit used above, for example, the resistance factor is $\frac{196}{286}$ = .685 and the inductance factor is $\frac{208}{286}$ = .727.

The resistance and inductance factors of a circuit vary with the size of wire and with the distance of separation. At 60 cycles with centers 12 inches or more the resistance factor is the higher for the sizes of conductor smaller than # 0 and the inductance factor is the higher for the sizes of conductor larger than # 0.

$$(\text{Resistance factor})^2 + (\text{Inductance factor})^2 = 1.$$

The power consumed in a circuit is the product of the current by the impedance volts and by the resistance factor. If the loop forming a circuit were closed at the remote end, the power factor of the circuit would be the same as its resistance factor.

The values of inductance factor which correspond to various common values of resistance (or power) factor appear in the following table:

Resistance (or power) factor..........	50	60	65	70	75	80	85	90	95	97.5	100
Inductance factor...	86.6	80	76	71	66	60	53	44	31	22.2	0

Calculation of Line Pressure Drop. — The total pressure drop in a circuit is determined from the resistance and inductance components in conjunction with the power factor of the load which the circuit is carrying. The drop is greatest at power factors which are near the resistance factor of the circuit. If a certain load draws 100 amperes at 70 per cent power factor over a # 0 circuit having a resistance factor of 68.5 per cent, the net fall of pressure between the point of supply and point of delivery will be greater than it is with the same current on the circuit at 100 per cent power factor.

Referring to Fig. 194, let the line OE represent the pressure delivered at the terminals of an induction motor. OR is the component of OE, which is doing useful work. ER is the wattless component of self-induction which causes the current through the motor to be out of phase with the impressed voltage.

EL is the resistance component and LP is the inductive component of the line drop. The resistance component of the line drop EL and the power component of the impressed

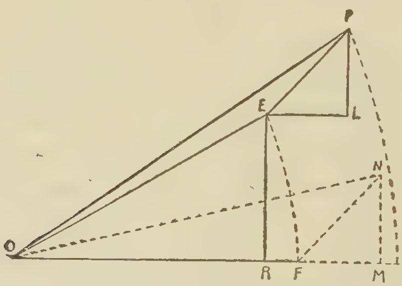


Fig. 194. Effect of Power Factor on Line Drop.

voltage OR are in phase with each other and the inductive components ER and LP are in phase with each other.

The resultant OP is the bus pressure necessary to deliver a pressure OE at the motor terminals. The net line drop is therefore the difference between OP and OE.

With noninductive load, such as incandescent lamps, ER disappears and the impressed pressure on the lamps takes the position of OF ($= OE$). The generated pressure necessary to deliver OF at the lamps is ON and the drop is the difference between ON and OF.

For example, assume an inductive load of 100 amperes at 2200 volts single phase, delivered at the end of a two-wire line of # 0 wire 4500 feet long with wires 12 inches apart, a frequency of 60 and a power factor of 80 per cent. The power

factor of the load being 80 per cent, we find by reference to the above table that the corresponding inductance factor is 60 per cent.

$$OR \text{ is } .80 \times 2200 = 1760 \text{ volts.}$$
$$ER \text{ is } .6 \times 2200 = 1320 \text{ volts.}$$

By reference to the foregoing table we find that the resistance drop per 1000 feet per ampere for # 0 is .098 volt. Hence the resistance drop is $.098 \times 4.5 \times 100 = 44.0$ volts for each wire. There being two wires, EL is $2 \times 44 = 88$ volts.

The inductive drop per 1000 feet per ampere for 12-inch centers is .104 volt and LP is $2 \times .104 \times 4.5 \times 100 = 93$ volts. The power and resistance component is $OR + EL$ or $1760 + 88 = 1848$ volts and the inductive component is $ER + LP$ or $1320 + 93 = 1413$ volts.

The resultant of these is

$$OP = \sqrt{(1848)^2 + (1413)^2} = 2332 \text{ volts.}$$

This is the pressure necessary to deliver 2200 volts at the end of the line. The drop is therefore the difference, or 132 volts, with a load of 100 amperes at 80 per cent power factor.

If a lighting load of 100 amperes at 100 per cent power factor were being carried, the inductance factor ER is zero, and ON is

$$\sqrt{(2288)^2 + (93)^2} = 2292 \text{ volts.}$$

The drop is therefore 92 volts, with a load of 100 amperes at 100 per cent power factor.

Mershon Diagram. — The calculations required for the solution of practical problems being rather cumbersome, Mershon has devised a diagram by which calculations which do not involve charging current may be made with greater facility and yet with sufficient accuracy for all ordinary purposes.

This diagram is presented in Fig. 195 and is based on the principles of the diagram of Fig. 194. The concentric circles are described about a center off the diagram which corresponds to the point O in Fig. 194. The divisions are made in percentages so as to make the scale applicable to all voltages.

The use of the chart may be illustrated by the foregoing circuit of # 0, carrying a load of 100 amperes at a distance of 4500 feet. The ohmic drop, being 88 volts, is 4 per cent, while the inductive drop is 4.2 per cent. The power factor was assumed at 80 per cent or .8. The base of the .8 power factor line in Fig. 195 is the point R in Fig. 194. The point where the .8 power factor line intersects the first circle is the point E in Fig. 194. Passing to the right 4 divisions and then up 4.2 divisions a point is reached which is about midway between the 5 per cent and 6 per cent circle. This point is equivalent to the point D in Fig. 194. The pressure necessary to deliver 100 per cent pressure at the end of the circuit is 105.5 per cent. The drop is 5.5 per cent of 2200, or 121 volts. The result may be gotten more accurately if desired by multiplying the percentages of drop by two or three before applying them to the diagram, and then dividing the result by the same multiplier. For instance, multiplying by three in this case, the ohmic drop is 12 per cent and the inductive drop is 12.9 per cent. Passing to the right 12.0 divisions and upwards 12.9 divisions, we reach a point corresponding to 17.5 per cent. Dividing by three the drop is 5.8 per cent, or 128 volts, as compared with 132 volts determined by calculation.

If the load on the circuit has a power factor of 100 per cent one begins at the base of the 100 per cent P.F. line, passes to the right 12.0 divisions and up 12.9 divisions. The point is on the 13 per cent circle. Dividing by three the drop is 4.33 per cent, or about 93 volts, as compared with 92 volts calculated.

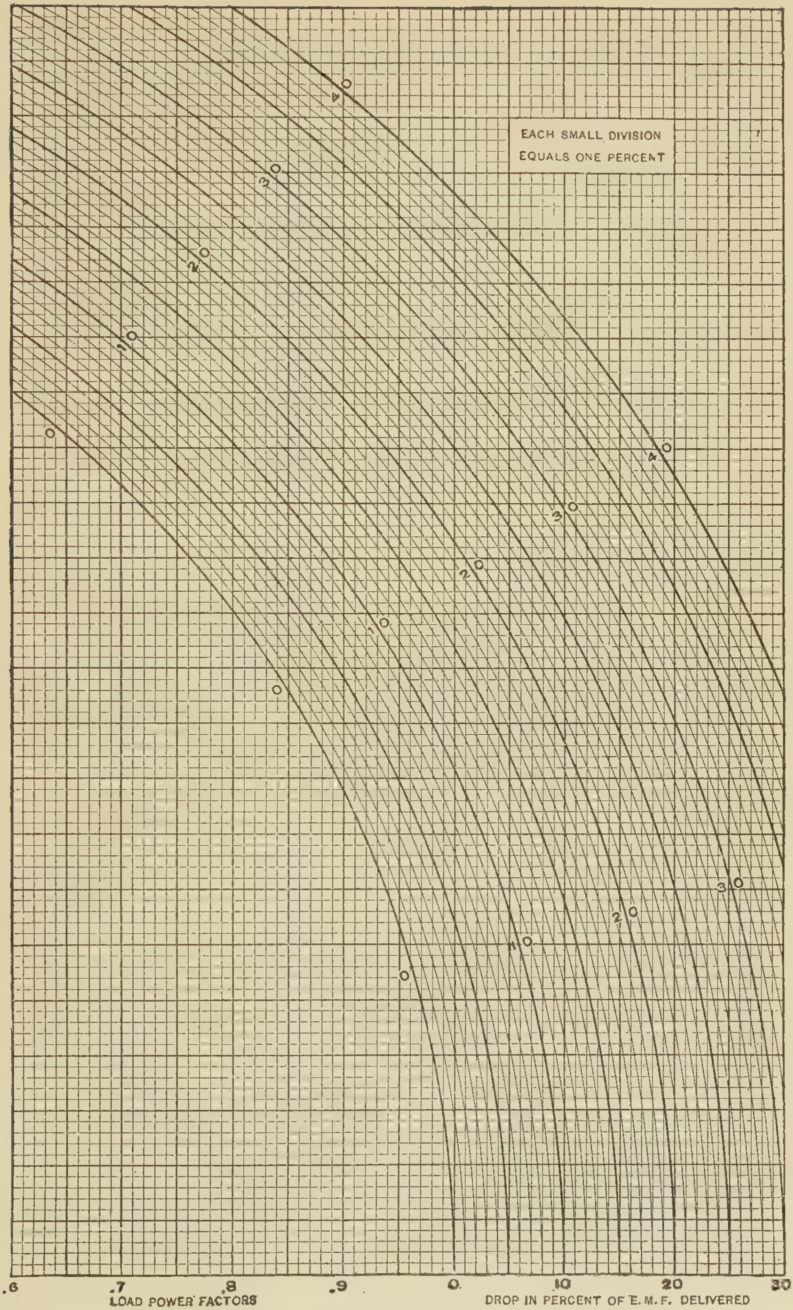


Fig. 195. Mershon Diagram for Calculation of Line Drop.

Two-phase Line Drop. — In the case of a two-phase four-wire circuit the drop is figured for one wire and multiplied by two, as in the case of the single-phase circuit.

On a three-wire two-phase feeder, the drop is different on the two phases, even with balanced load, since the current in the neutral wire is the resultant of those in the phase wires and the drop on the neutral wire affects the two phases differently.

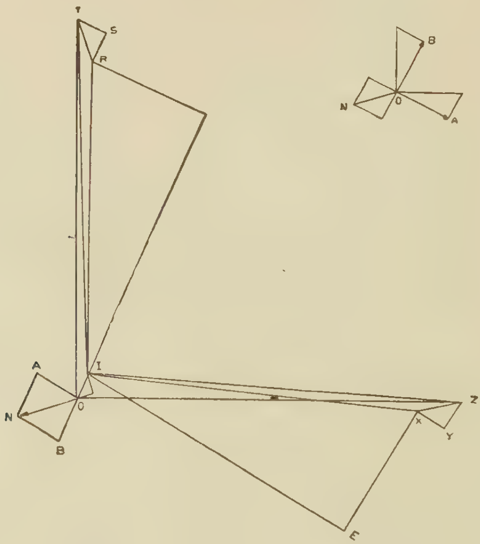


Fig. 196. Drop in Two-phase Circuit.

The amount of this difference varies with the power factor of the load, and is, of course, further affected by unbalanced load.

In Fig. 196 the smaller diagram in the upper corner shows the current relations at a power factor of 90 per cent with balanced load, the current on phase A being OA, that on phase B being OB and that on the neutral conductor being ON. In case of unbalanced load, the neutral current swings around to a position more nearly in opposition to the current on the phase which carries the heavier load.

The drop on each of the wires is determined as it would be for a single wire of a single-phase conduit.

Thus if the circuit is of three # 0 wires carrying 100 amperes on the phases and 141 amperes on the neutral, the ohmic component of drop on the phase wires at 5000 feet is $100 \times 5 \times .098 = 49$ volts and the inductive component is $100 \times 5 \times .104 = 52$ volts. On the neutral wire this ohmic component is $141 \times 5 \times .098 = 69$ volts and the inductive component is $141 \times 5 \times .104 = 73$ volts.

The relation of these is such that direct calculation of the resultant drop at a given power factor of the load is very complicated. It may, however, be laid out graphically in such a way as to indicate the relation very clearly and to give approximate numerical results. This is done in the larger diagram in Fig. 196.

The current on phase A is represented by OA which is laid out at an angle with OZ corresponding to a power factor of 90 per cent. This is combined with OB, the current on B phase, to determine the current ON on the neutral conductor.

The drop on the neutral wire is represented by OI, the resultant of the ohmic and the inductive components.

The drop on the phase wire is represented by XZ, made up of the ohmic component XY and the inductive YZ.

The triangle IEX represents the pressure absorbed by the load at 90 per cent power factor and IX is the pressure delivered at the end of the line. The pressure impressed at the point of supply is OZ and the drop is the difference between OZ and IX.

Similarly the drop on phase B is the difference between IR and OT. It is apparent that these differences are not equal, the drop on A phase being less than that on B phase.

The construction of the diagram is a cut and try process, since the power factor is modified somewhat by the inductive drop of the line wires, and the phase position of OI is shifted

somewhat thereby. Fortunately, the use of such a diagram is not necessary where line drop compensators are used in each wire as they make due allowance for changes in balance, changes in load and in power factor. It is only necessary to determine the values of XYZ, RST and OCI at the rated full load of the current transformers supplying the compensator, as described in the chapter on Voltage Regulation.

Drop in Three-phase Circuits. — In a three-phase circuit made up of three conductors symmetrically arranged in a triangle and carrying a balanced load, the inductive effect is the same in each wire and the calculation of drop may be made as easily as for a single-phase circuit.

The ohmic drop in each wire is in phase with its current, but as the currents in the three wires are 120° apart the ohmic drop for the two wires making up any phase is not twice that of one wire, as it is in the single-phase circuit, but is 1.73 times this drop. Likewise the inductive component, which is 90° behind the current, is 1.73 times that of a single wire for the loop.

These values are readily found from the reactances and resistances given in the table, and the known values of current, size of wire and length of circuit. The percentages may then be applied to the Mershon diagram.

For example, if the # 0 circuit 4500 feet long carrying 100 amperes at 60 cycles and 12 inches separation were a three-wire three-phase circuit, the ohmic drop would be as in the single-phase circuit, $100 \times .098 \times 4.5 = 44$ volts per wire.

The drop in two wires of either phase would be $44 \times 1.73 = 76$ volts. This is $\frac{76}{2200} = 3.4$ per cent.

The inductive component *per wire* is $100 \times .104 \times 4.5 = 47$ volts, and for the loop $47 \times 1.73 = 81$ volts, or $\frac{81}{2200} = 3.7$ per cent.

Applying these percentages to the Mershon diagram we

find the drop at 80 per cent power factor is 5 per cent of 2200, or 110 volts.

If the load in kilowatts on the three-phase circuit were the same as on the single-phase circuit, the current per wire on the three-phase circuit would be $\frac{100 \times 1.73}{3} = 58.0$ amperes, and the drop at 58 amperes on the three-phase circuit would be $\frac{58}{100}$ of 5 per cent, or 2.9 per cent.

The single-phase drop at the same load was found to be 5.8 per cent, or twice the three-phase drop.

Therefore for the same load and equal line drop, the size of the conductor in a three-phase circuit may be just half that of a single-phase circuit.

There being three wires in the three-phase circuit, it follows that the weight of copper required for a three-phase circuit is three-quarters of that required for a single-phase transmission, other things being equal.

Therefore, if calculation shows that a certain sized conductor will carry a *given load* at a *given line drop*, *single phase*, it follows that *three* conductors of *one-half* that size will carry the *same* load at the *same drop*, *three phase*, if the load is balanced.

Nonsymmetrical Arrangement. — When the arrangement of conductors is not symmetrical, the inductive component is different between different pairs of wires, on account of the different distances between centers. The most common case is that in which the wires are arranged on a cross arm in the same horizontal plane, as is common practice in distribution circuits, and to some extent in transmission circuits. In such cases the equivalent of a symmetrical arrangement can be secured by transposing the conductors at proper intervals. Figure 197 shows a circuit transposed at two points, so as to produce a complete spiral of the line. This is not required in

2200-volt distributing feeders which are equipped with line-drop compensators, as the compensation can easily be adjusted to correct unbalanced inductive conditions of this sort.

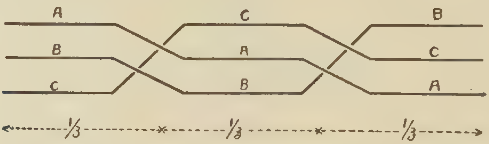


Fig. 197. Transposition of Three-phase Circuit.

Unbalanced Three-wire Three-phase Circuits. — The calculation of drop in an unbalanced three-wire three-phase circuit is somewhat complicated and such problems are most readily solved graphically. Unbalanced loads which are not more than 10 to 15 per cent from one another may usually be averaged and considered as balanced for practical purposes.

One of the most common conditions of this sort is found in systems where the lighting is all on one phase of the feeder and the third wire carries a small scattered load of three-phase power. Under these conditions the lighting phase may be considered as a single-phase circuit, as the current in the two conductors that make the lighting phase is much greater than it is in the other conductor, and the drop due to the lighting phase current is but little out of phase with the pressure which produces it.

However, as the power load increases the current in the conductors of the lighting phase pulls more and more out of phase with the lighting pressure, and the drop on the lighting phase becomes less and less for a given current value, until finally, when the current on the power phases equals that on the lighting phase, the drop on the lighting phase is but 86.6 per cent of what it would be with the same amount of current carried as lighting only.

That is, if 100 amperes on the lighting conductors produced a drop on the lighting phase of 10 per cent when there is no power load on the feeder, the drop with 100 amperes on each conductor will be only 8.66 per cent.

In practice this relation will not hold exactly, on account of the fact that the power factor of the lighting load is usually 95 per cent or higher, while that of the power load is 75 per cent to 80 per cent. This tends to make the current in one of the lighting phase conductors somewhat lower and that in the other lighting phase conductor somewhat higher than it would be if the power factor were the same in all phases. However, the reduction in the drop on the lighting phase is not sufficient ordinarily to interfere with the regulation of the lighting phase until the current on the power conductor reaches a point where it is more than 30 per cent of the average current on the lighting conductors.

Four-wire Three-phase Line Drop. — The working pressure at the receiving devices in such systems is the star pressure, that is, the pressure between phase wires and neutral. When the star pressure is 2200 volts, the pressure across phase wires is $2200 \times 1.73 = 3800$ volts.

With balanced load the neutral conductor carries no current and the drop is that in the phase wire only. The drop at 100 amperes on a # 0 circuit 4500 feet long is $100 \times 4.5 \times .098 = 44$ volts. This is 2 per cent of 2200 volts. Likewise the inductive component is $100 \times 4.5 \times .104 = 47$ volts, or 2.1 per cent. At 80 per cent power factor, by the Mershon diagram the drop is 3 per cent.

As in the balanced three-wire circuit the size of wire for a given load and drop is just *half* what it would be for a *single-phase* circuit, and the *distance* may be halved and the calculation made as for a single-phase circuit if desired.

In the case of an unbalanced four-wire circuit, which is the

more usual condition, the effect of the drop on the neutral wire must be taken into consideration. This varies with the proportion of unbalance and requires a graphical solution.

In general the effect of the unbalance is to increase the drop on the more heavily loaded phases and to make it less than it would be at balanced load on the lighter loaded phases.

The proportions of the diagram, Fig. 198, are based on calculations for a circuit having an ohmic drop of 15 per cent,

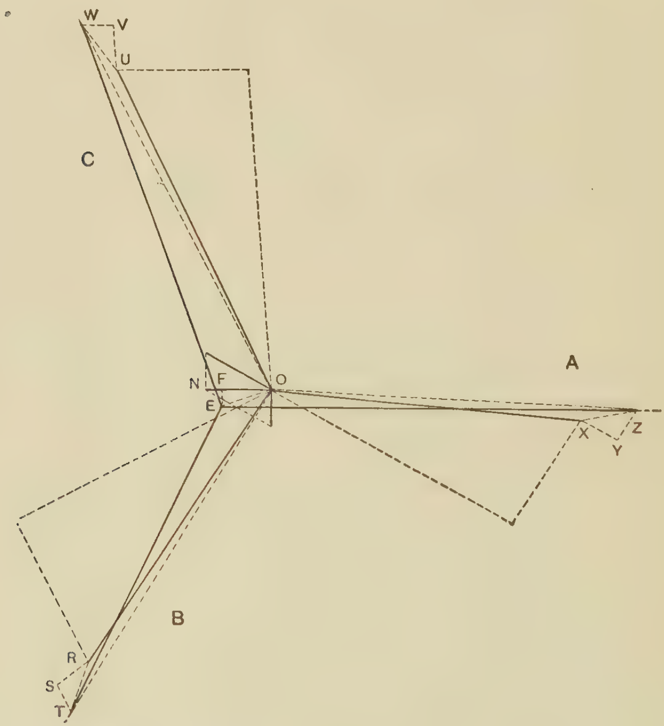


Fig. 198. Drop on Three-phase Four-wire Circuit.

an inductive drop of 10 per cent and loads on the three phases in the ratio of 60, 80 and 100, on A, B and C respectively.

The current ON on the neutral conductor is the resultant

of an unbalance of 20 on B and 40 on C. This fixes the phase of the neutral current and hence of the drop in the neutral conductor. The triangle OEF represents the ohmic and inductive components of the neutral drop.

The drop on the phase wires is represented by the triangle at the outer ends of the phase vectors. These are proportional to the drop in the phase conductor (single distance only). The vector sum of the phase drop and of the neutral drop is the total loss of pressure at the end of the circuit. For instance, the net drop on A phase is the difference between the impressed pressure EZ and the delivered pressure OX. Similarly the drop on B phase is $ET - OR$, and that on C phase is $EW - OU$.

Where line-drop compensators are employed in each conductor the only calculations required are those for the four individual conductors, and the use of a diagram to get the combined effect is unnecessary. The importance of equipping the neutral conductor with a line-drop compensator is readily apparent from the diagram.

It is difficult to get accurate results from the diagram except when drawn to a large scale, and as the phase of the neutral current shifts hourly with different conditions of balance it is impossible to properly regulate unbalanced four-wire circuits by a schedule of volts and amperes, as is sometimes done with single-phase circuits.

Mutual Induction. — Where several alternating-current circuits are carried on the same poles there is an inductive reaction between them which is proportional to the current flowing and depends on the relative proximity of the circuits. That reaction is known as *mutual induction*, as the current in one circuit affects the voltage on the other, and *vice versa*. Mutual induction is a magnetic effect of the same nature as self-induction. The magnetic field due to the current in cir-

cuit A sets up an electromotive force in circuit B which is proportional to the volume of current in circuit A and the distance between them. Circuit B's field affects circuit A's pressure likewise. The electromotive force of mutual induction is a quarter cycle behind the current which produces it, and its phase must be taken into account in determining the effect.

The mutual induction voltages are so small at the ordinary current values at primary distributing voltages that they can be neglected, but where distribution is effected by means of circuits operating at voltages less than 300 which involve heavy currents, mutual induction is likely to be very troublesome. Its effect can be largely offset by making the distance between circuits as large as possible and by so arranging the conductors that as little of the magnetic flux of one circuit may be linked with another as possible. Circuits may also be transposed at intervals, so that the mutual induction set up in one part of the circuit is offset by the mutual induction in the opposite sense in another section of the circuit.

With three-phase circuits this should be done twice, so as to make a complete spiral turn of the three wires.

The effect of a transmission line on a telephone circuit run parallel to it is usually such that numerous transpositions must be made in the telephone circuit to prevent inductive disturbances which make the telephone line noisy.

Underground circuits run in separate ducts are not usually sufficiently affected to make any appreciable disturbance.

Skin Effect. — Another condition which affects the pressure drop on alternating-current circuits is known as the *skin effect*. This is found in cables of large cross-section and is due to the fact that the currents passing through the strands around the outer surface of the cable induce a pressure in the strands near the center which opposes the flow of current

and causes the outer strands to carry the greater part of the load of the cable. In very large cables the current in the center strands is found to be so small that it is desirable to build up large cables about a core of nonconducting material. This puts the working metal near the outer layer and makes a more economical cable. Cables over 500,000 c.m. are often made in this manner where they are to be used on 60-cycle current, and over 1,000,000 c.m. on 25 cycles.

The rule for the calculation of the skin effect is a complicated one, as it involves the frequency, area of conductor, permeability of metal, temperature coefficient, etc. It is sufficient for general purposes to know that the skin effect is proportional to the product of the frequency by the circular mils. The higher this product, the more the resistance of the cable is increased by the skin effect. The resistance factors corresponding to various values of circular mils and frequency are given in the above table. To determine the skin effect of a copper cable having an area of 1,000,000 c.m., carrying current at 60 cycles, note the factor for copper opposite the product 60,000,000. The resistance factor is 1.096. The resistance of 1,000,000 c.m. cable to direct current at 68° F. being .0103, the effective resistance is .0103 × 1.096 =

SKIN-EFFECT COEFFICIENTS

Cir. mils × frequency	Coefficient		Cir. mils × frequency	Coefficient	
	Copper	Aluminum		Copper	Aluminum
10,000,000	1.000	1.000	80,000,000	1.158	1.069
20,000,000	1.008	1.000	90,000,000	1.195	1.085
30,000,000	1.025	1.006	100,000,000	1.23	1.104
40,000,000	1.045	1.015	125,000,000	1.332	1.151
50,000,000	1.07	1.026	150,000,000	1.433	1.206
60,000,000	1.096	1.04	175,000,000	1.53	1.266
70,000,000	1.126	1.053	200,000,000	1.622	1.33

.01129 when the cable carries alternating current at a frequency of 60 cycles. The resistance drop is increased 9.6 per cent by the skin effect in this size of cable.

Electrostatic Capacity. — Alternating-current circuits are subject to electrostatic-capacity phenomena which have an important bearing at the higher transmission voltages and frequencies. A line is charged and recharged with each alternation of the voltage. A charging current flows in such a circuit, which is proportional to the rate of change of the impressed voltage. The rate of change being greatest when the electromotive force wave is passing through zero, the charging current is at its maximum at that instant, and therefore is one-quarter cycle ahead of the impressed voltage wave. The charging current is a half cycle ahead of the inductive component, which is a quarter cycle behind the voltage wave, and therefore tends to neutralize the effect of self-induction. At ordinary distributing voltages and frequencies the capacity effect is too small to be of any consequence in the solution of line-drop problems and need not be considered.

At transmission voltages and distances it becomes a matter of considerable importance in some cases.

The charging current of a circuit varies with its electrostatic capacity, its length and the voltage and frequency at which it is operated.

The capacity of an overhead circuit is fixed by the distance between the conductors and by their size. With insulated conductors surrounded by a lead sheath, the capacity is further affected by the dielectric constant of the insulating material.

The capacity of a single-phase circuit strung in the open air per 1000 feet of circuit is $C = \dfrac{.003677}{\log \dfrac{D}{r}}$ microfarads, when

D is the distance between centers of conductors and r is half the diameter of the conductor. The logarithm is the common logarithm.

Calculation of Charging Current. — The charging current of a single-phase circuit is $I = \frac{6.28\, dfCE}{1{,}000{,}000}$ amperes, when d is the distance in thousands of feet, f is the frequency, C is the capacity and E is the voltage between conductors.

For example, in a circuit consisting of two # 0 B. & S. wires strung 60 inches apart, 200,000 feet in length and operated at 40,000 volts, and 60 cycles, the charging current would be

$$I = \frac{6.28 \times 200 \times 60 \times C \times 40{,}000}{1{,}000{,}000} \text{ amperes.}$$

$$C = \frac{.003677}{\log \frac{D}{r}} = \frac{.003677}{\log \frac{60}{.1625}} = .00143,$$

whence

$$I = \frac{6.28 \times 200 \times 60 \times .00143 \times 40{,}000}{1{,}000{,}000} = 4.33 \text{ amperes.}$$

The charging current of a three-phase circuit is $\frac{2}{\sqrt{3}} = 1.154$ times that of a similar single-phase circuit at the same voltage and frequency.

That is, if the # 0 circuit above referred to were a three-phase circuit operating at 40,000 volts with conductors equally spaced, the charging current would be

$$I = 1.154 \times 4.33 = 4.99 \text{ amperes.}$$

The charging current per 1000 feet of wire at 1000 volts three-phase line pressure is given in the following table for 60

cycles. The values at other voltages or frequencies are proportionately higher. At 40,000 volts, the values in the tables should be multiplied by 40, or at 25 cycles they are $\frac{25}{60}$ of those in the table.

The tendency of the charging current to raise the power factor of the line current tends to reduce the line drop where the load is of an inductive character. With very long lines and high voltages, it is not unusual to have a line charging current so high that the power factor is a leading one most

Charging Current Three-Phase Circuits in Air

Size of conductor	Amperes per 1000 feet, per 1000 volts, at 60 cycles						
	Distance between centers						
	$\frac{3}{4}$ in.	1 in.	24 in.	36 in.	48 in.	60 in.	72 in.
350,000	......	......	.000867	.000788	.000745	.00071	.000688
0,000	.00312	.0025	.000819	.000749	.000710	.000679	.000658
000	.00284	.00233	.000797	.000732	.000693	.000666	.000645
00	.0026	.00216	.000775	.000714	.000679	.000649	.000632
0	.00241	.00202	.000758	.000701	.000662	.000640	.000618
1	.00224	.0019	.000740	.000684	.000649	.000623	000605
2	.00209	.0018	.000719	.000666	.000636	.00061	.000592
4	.00185	.00161	.000688	.000640	.00061	.000588	.000571
6	.00165	.00146	.000645	.000605	.000575	.000557	.000544
8	.00150	.00134	.000623	.000579	.000557	.000540	.000523
10	.00137	.00124	.000597	.000562	.000536	.000523	.000510

of the time. With an 80-mile line operating at 60,000 volts, 60 cycles, it requires an inductive load of about 2800 kv-a. at 80 per cent power factor to neutralize the line charging current. At loads less than 3000 kv-a. the power factor would be leading and the inductive component of the line drop would tend to raise the power factor. The charging current of long high-voltage lines fixes the minimum size of the generating and transforming equipment in some cases. For in-

stance, a generating station supplying an 80-mile 60,000-volt line should not have a generator rated at less than 1500 to 2000 kv-a., as the line charging current is about 1600 kv-a. and it would be impossible to excite the line at full pressure from a smaller machine running singly without overloading it.

Charging Current of Cables. — In underground cable work the effect of charging current is greatly increased by the reduced separation of polarities while the inductive effect is correspondingly decreased thereby. The charging current can be determined by the use of the formula given in Chapter XII.

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